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Council for Scientific and Industrial Research

BULLETIN No. 229

Studies in Cement-Aggregate Reaction

I. Australian aggregates and cements

By

A. R. ALDERMAN, PH.D., D.SC.,
A. J. GASKIN, M.SC.,
R. H. JONES, B.SC.,
and
H. E. VIVIAN, B.SC.AGR.

II. The effect of alkali movement in hardened mortar

By

H. E. VIVIAN, B.SC.AGR.

III. The effect of void space on mortar expansion

By

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IV. The effect of expansion on the tensile strength of mortar

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V. The effect of void space on the tensile strength changes of mortar

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VI. The effect of carbon dioxide

By

A. J. GASKIN, M.SC.

MELBOURNE, 1947

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FOREWORD

In 1942 the Cement and Concrete Association of Australia entered into an agreement with the Council to support research work on cement and concrete for a period of five years. The agreement has recently been renewed for a second similar period.

This Bulletin describes part of the work on what has been the main project during the first period of five years. One of the immediate results of the investigation is that Australians know with much more certainty what aggregate materials to avoid in concrete structures. Some materials which it was proposed to use in certain large concrete structures have been shown to be unsuitable, and probable costly failures in future years can thus be avoided. For these reasons the work is already returning large dividends.

In addition to classifying available aggregate materials, the investigators have developed rapid methods of identifying unsuitable aggregates. They have studied the causes of concrete failures when such aggregates are used. This more fundamental work is still proceeding and will be the subject of further papers. It is on such investigations that future advances in the use of concrete will be based.

I. W. WARK,
Chief, Division of Industrial Chemistry.

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Studies in Cement-Aggregate Reaction*

I. Australian Aggregates and Cements

By A. R. Alderman, Ph.D., D.Sc., A. J. Gaskin, M.Sc., R. H. Jones, B.Sc., and H. E. Vivian, B.Sc.Agr.†

Summary

A wide variety of Australian aggregates and cements has been examined with a view to estimating the possible incidence of expansive reaction in concrete made from these materials.

Mortar-bars have been observed over periods up to two years and the results correlated with petrographic examination of the aggregates and chemical composition of the cements. This correlation has shown that in most cases the potential reactivity of aggregates can be assessed by petrographic examination but that doubtful material requires supplementary mortar tests.

1. Introduction

Interest in the problem of expansive reaction in concrete was aroused in 1940 when T. E. Stanton claimed that the use of certain aggregates with cement rich in the alkali metals had produced deterioration in concrete structures. These aggregates were all rocks or sands containing opal. It was suggested that reactions between opal and alkali compounds derived from the cement produced expansion and consequent cracking of concrete.

Many papers on the subject have since been published. Most of these are concerned with the incidence of the problem in the United States of America and include accounts of descriptive and experimental work on American concrete materials. These also suggest that the geographical aspect of the problem is important. Precautions in choosing materials for aggregates are necessary in those areas in California which are occupied by rocks of the Miocene Monterey Series. These rocks, which contain opal, have been shown by Stanton to be particularly reactive when used as aggregates with high-alkali cement. Tremper (1941) has shown that similar precautions are necessary in certain areas of the State of Washington. Geographical and geological aspects of the problem are particularly important in countries, such as Australia, where a single extensive geological formation may constitute all the rock outcrops and thus the only readily available source of aggregate over a very wide area.

It was desirable therefore to investigate the probable incidence of this problem in Australia. Such an investigation may best be approached in two ways, firstly by an examination of the materials concerned and their reactions with one another, secondly by a more fundamental investigation of the mechanism of these reactions. This paper is largely concerned with an investigation of Australian aggregate materials and their behaviour when used in concrete with a variety of commercial cements.

* Typescript received May 16, 1947.

† Officers of the Division of Industrial Chemistry.

2. Plan of Investigation

Before laboratory investigations were begun, literature on the subject was reviewed (Alderman, 1943) and methods examined. As no rapid method appeared to give reliable results it was decided to follow, with but few modifications, that of T. E. Stanton (1940) which involved the making of mortar bars, their storage in moist air in sealed containers, and their periodical examination and measurement.

Altogether 67 samples of Australian aggregates were obtained. These included materials used extensively in all Australian States except Western Australia, from which State samples could not conveniently be obtained. Other materials, although not used commercially as aggregates, were included because they were likely to give interesting results. As will be seen later, the petrographic range of these aggregates is very wide. The sixteen cements used were obtained from ten Australian manufacturers. As it was considered impracticable to test every aggregate with every cement, each aggregate, when a sufficient quantity was available, was tested with at least four cements of varying alkali content. As most Australian cements are used only in the State in which they are manufactured, it was possible to arrange the cement-aggregate combinations on a geographical basis so that each aggregate was tested with all the cements with which it was likely to be used. Some aggregates which appeared more likely to react were tested with a larger number of cements. In addition, two cements, one high (designated A) and the other low (P) in total alkalis, were used with each aggregate and they thus provided standards for comparing aggregates. Also, two aggregates, one a reactive siliceous magnesian limestone from California (Z2), and the other, an inert quartz sand from Leighton Buzzard, England (Z1), were used with each cement, and so provided standards for comparing the various cements.

The conditions of fabrication, storage, and measurement of test bars were standardized as far as practicable. Although examination of the surface of test bars gave some information concerning the reactive condition of the mortar, periodical measurement was regarded as the most important indication of this property.

Preliminary work consisted of chemical analysis of each cement used in the investigation and petrographic examination of each aggregate. In order to increase the probability of samples of both cements and aggregates being typical of their sources, two series of test bars were made, duplicates being tested in each series. After two mortar bars of each cement-aggregate combination had been fabricated, new samples of each cement and aggregate were obtained whenever possible and the second series of duplicate bars was made. Thus four bars of most combinations were made.

These investigations on cement-aggregate reaction were designed to give a broad survey of the behaviour of Australian concrete materials and an estimate of the possible importance of the problem in Australia. The standard procedure used throughout this work was adopted because it appeared likely to give the most reliable results, it was suitable for the examination of a large number of specimens and the necessary equipment was available. It was realized that the standardized conditions would not be ideal for all the materials which were to be used but that examination of important variables such as

cement-aggregate ratio, water-cement ratio, temperature of storage, &c., could best be made as subsidiary investigations and be the subject of separate reports. From this work as well as from other methods of investigation, much information has been accumulated about more fundamental aspects of cement-aggregate reaction.

3. Materials and Methods

(i) *Cement*

The cements supplied by ten Australian manufacturing companies were of two types, Ordinary Portland and Low Heat. Whenever possible two different samples of each cement were obtained and were used to test two different samples of each aggregate. The chemical compositions of the cements as determined in this laboratory are given in Appendix II. Particular attention was paid to the determination of Na_2O and K_2O, a modification of the Glaze (1931) method being used. The total alkali oxide content, which was calculated as sodium oxide ($Na_2O + 0{\cdot}658\ K_2O$), differed widely in the sixteen cements and ranged from 0·12 to 1·09 per cent. in the first series of samples, and from 0·15 to 0·98 per cent. in the second.

Although it is generally assumed that alkali content is the most important characteristic of the cement in promoting expansion with a reactive aggregate, there can be no doubt that there are other modifying factors. Apart from other variations in chemical composition, physical variations have marked effects. It has been shown by Blanks and Meissner (1946) that the fineness of the cement has an important effect on rate of reaction.

As the object of the present work was to investigate the possible reactivity of Australian aggregates with commercial cements, no special treatment was given to the cements used for making test bars.

(ii) *Aggregates*

Aggregates were received in the form of crushed stone, screenings, gravel, or sand. All were submitted to a routine petrographic examination. In addition to the examination of thin sections under the microscope, particular attention was given to the recognition of opaline silica. For this purpose the alkali hydroxide etching technique of Parsons and Insley (1944) was tried, but difficulty was found in estimating the degree of etching in fine-grained and in slightly decomposed rock minerals. Immersion of etched and washed sections in methylene blue solution effectively defined gel-covered opaline minerals but could not be applied to most rocks because of the absorption of dye by decomposed minerals such as kaolinized feldspar and slightly bleached biotite. Confirmation of the presence of opal was obtained by microscopic examination of the powdered aggregate immersed in a liquid of suitable refractive index (e.g. 1·47).

Specific gravity methods were found to be useful in separating the light fraction of some aggregates, in which as little as 0·01 per cent. of opal could sometimes be estimated. After crushing and sieving through a 72-mesh B.S. sieve, the fine material was suspended in a bromoform-alcohol mixture of density 2·36 and centrifuged. The light fraction was then collected, washed with alcohol, dried, weighed, and

examined under the miscroscope. In other cases, the effectiveness of this test was limited by the fact that opal occurred in the aggregate as fine films surrounding other minerals. In such rocks microscopical examination and mortar tests clearly indicated the presence of opal, but bromoform treatment failed to give satisfactory separation of this mineral. Grinding to 200 mesh B.S.S. did not overcome this difficulty since the fine particles tended to pack together under the influence of surface forces and a clean separation could not be achieved. An example is a siliceous magnesian limestone from California (Z2), in which the opal appeared from microscopic examination to be dispersed in very fine films and stringers throughout the rock. By contrast, in a siliceous "gibber"* from Oodnadatta, South Australia (S14), the opal was confined to relatively large well-developed veins. Only a small fraction of the finely dispersed opal in the Californian rock was separated by bromoform, whereas, owing to its relative coarseness, the opal in the "gibber" was more completely separated. Until these facts were shown by applying alkali etch and dye absorption tests, the reason for discrepancies between mortar bar expansions and opal content as determined by bromoform separation was not obvious.

The bromoform separation almost invariably produced an appreciable light fraction from basic igneous rocks. Microscopical examination showed that this generally consisted of yellow-green particles of minerals of the saponite type. These do not appear to react with high-alkali cement.

In several aggregates which reacted with high alkali cement it was not possible to identify any material, such as opal, which had been found by previous workers to be reactive. These aggregates all showed "delayed" reaction which did not appear until the mortar was about a year old. The reactive material seemed to be cryptocrystalline silica which was first thought to be chalcedony. Chalcedony, the "chalcedonite" of Winchell (1933), has an average refractive index $n = 1{\cdot}533$, which is lower than the corresponding index of quartz which is 1·547. The refractive index of the cryptocrystalline silica in these aggregates was determined and found to be that of quartz. Thus this material must be called cryptocrystalline quartz. Opal could conceivably be intergrown with the quartz but very careful microscopic examination did not disclose it.

Many of the sands, sandstones, and quartzites examined contained fine quartz, mostly microcrystalline, but which in places could be called cryptocrystalline, but they did not react. Recognition of potentially reactive material of this kind is thus still difficult.

Brief petrographic descriptions of all the aggregates are given in Appendix III. Each aggregate has been given a reference letter and number, the letter referring to the State whence it came. Thus Q indicates Queensland, N—New South Wales, V—Victoria, T—Tasmania, S—South Australia, NT—Northern Territory, and Z—non-Australian.

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* The term "gibber" is applied to the loose pebbles and boulders which are a very common surface feature of the desert plains of the Australian central regions. They have frequently undergone extreme secondary silicification.

The wide petrographic range of aggregates is shown by the following list which will also serve as a petrographic index to Appendix III.:—

Quartz Sands and Gravels: Q3, V10–15, T1, T3, T9, S2, S6–10, S17, NT6, Z1.

Feldspathic Sands and Gravels: Q1–2, Q5, N1, NT5.

Ferruginous Gravels: Q11, NT2–4.

Sands and Gravels with Opal or Cryptocrystalline Silica: T7–8, S14, NT7–8.

Quartzites: T6, S1, S11–12.

Feldspathic Quartzite: S16.

Opaline Quartzite: S15.

Sandstone: NT1.

Limestone: S5.

Opaline Limestone: Z2.

Granites: Q7–8, V9.

Toscanite: V8.

Quartz–Feldspar–Porphyry: Q6.

Tracnyte: Q9.

Andesite: N2.

Silicified Andesite (Porphyrite): Q4.

Diorite (Porphyrite): Q10.

Dolerites: N3, T2, T4–5.

Basalts: N4, V1–7.

Basaltic Scoria: V16.

Volcanic Breccia: N6.

Opal: V17.

Slag: N5.

(iii) *Fabrication, Storage, and Measurement of Mortar Bars*

Samples of aggregates received in the form of crushed stone or screenings were reduced in size by passing consecutively through a jaw crusher, crushing rolls, and a disc pulverizer. They were then sieved and the fraction between 18–52 B.S.S. mesh was used for fabricating test bars. Natural gravels, which frequently contain particles of all sizes from large pebbles to fine sand, were passed through a jaw crusher and crushing rolls, and were used without further treatment, as it was considered desirable to retain the fine sand. Sands which contained no undesirably large particles were not treated in any way before use.

Following Stanton's recommendations, all test bars were made up with a cement-aggregate ratio of 1 : 2 by weight. The water-cement ratio was approximately 0·4 to 0·5 : 1 depending on the nature of the aggregate, the aim being to produce mortars of similar consistency. Distilled water was used throughout. The moulds and length comparator used for fabrication and measurement of mortar bars were similar to those recommended for the autoclave expansion test of Portland cement (A.S.T.M. designation No. C151–40T).

Standard procedure was followed in mixing the mortar and in moulding test bars. Water was added to the dry mixture of cement and aggregate and the whole mixed for two minutes to produce a uniform paste. This was placed in the greased mould in three layers each being carefully pressed down, especially in the corners and around the gauge points. The surface of the mortar was smoothed lightly. When complete the mould was stored in a moist cabinet at 21°C. (70°F.) for 20 hours. The test bars were then suitably marked and removed from the mould. Each bar measured 1 in. by 1 in. by 11¼ in. but the effective length of mortar between the stainless steel gauge points was 10 in.

After measurement the bars were stored vertically in glass or metal containers which had tight fitting lids and in which the air was kept moist by means of an open beaker of water. The containers were stored at room temperature which in Melbourne has a yearly mean of 58·5°F. Measurements were made at 28-day intervals for the first six months, and at 56-day intervals for twelve months, after which the intervals were increased to 84 days. In making these measurements, which were correct to 0·0001 inch, bars were measured and replaced within five minutes of removal from the container.

Storage at room temperature was adopted because of convenience and approximation to service conditions. Although a special series of bars has been stored at a constant higher temperature of 43°C. (110°F.) the practice suffers from various disadvantages as pointed out by Blanks and Meissner (1946, page 522). It would appear that the best method for most purposes would be to keep both storage containers and micrometer at a constant temperature such as 21°C. (70°F.). The main disadvantages resulting from storage at uncontrolled temperature lie in the variations in the length of bars produced by changes in temperature which also affect the humidity in the container. The direct effects of change in temperature can be minimized by frequent checking of the zero reading of the micrometer by reference to the length of the standard stainless steel bar, also kept at room temperature. Change in humidity due to temperature variations is probably a more important factor. Despite the presence of a free surface of water in each container, there is likely to be a lag in the adjustment of the air to saturation. Control bars, however, made with standard non-reactive sand, showed that length variations due to these factors are small compared with those produced by expansive reaction. The graphs given in Figs. 1 and 2 illustrate this point.

In addition to the test bars, small mortar blocks were made of each aggregate with a high-alkali cement (A) and a low-alkali cement (P). These blocks, stored under conditions similar to those of the larger test bars, were broken periodically and their broken surfaces examined with a binocular microscope. By this means the behaviour of aggregate particles was observed and signs of reaction noted. Spots of wet gel-like material surrounding these particles generally indicated that the aggregate was reactive even though the mortar may not have expanded significantly.

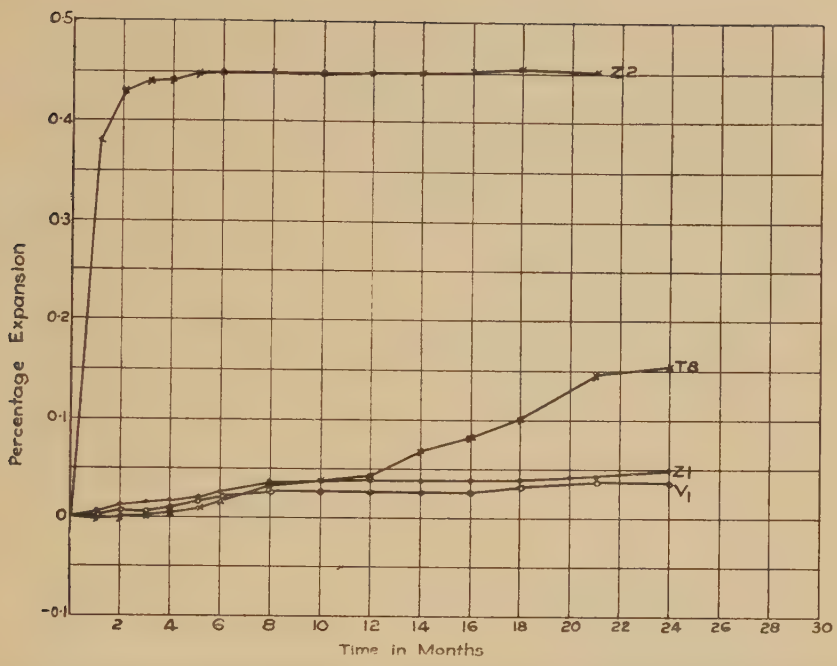

FIG. 1.—Showing the expansion of mortars made from high-alkali cement A and four aggregates.

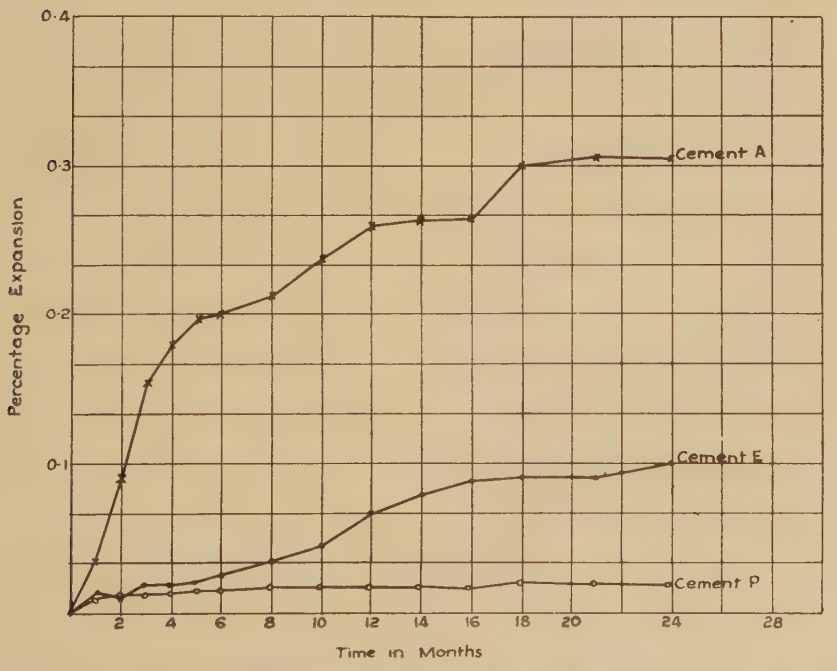

FIG. 2.—Showing the expansion of mortars made from reactive aggregate S15 and three cements, A, E, and P.

4. Results and Discussion

The results of observations on test bars and the correlation of aggregates and cements with reactivity are given in summarized form in Appendix I., and in still shorter form in Table 1 in which the expansions, after 24 months, of mortars made from each aggregate with each of the two cements (A and P) are given. Appendix I. is arranged so that the various mortars made from each aggregate are grouped together. The aggregates are listed on the same geographical basis as in Appendix III. in which the petrographic nature of each aggregate is briefly described.

TABLE 1.—MEAN LINEAR EXPANSIONS EXPRESSED AS HUNDREDTHS OF 1 PER CENT. OF 1 : 2 MORTAR BARS AFTER 24 MONTHS' STORAGE IN MOIST AIR. THESE EXPANSIONS ARE GIVEN FOR MORTARS MADE FROM EACH AGGREGATE WITH TWO CEMENTS.

Aggregate	High-Alkali Cement A.		Low-Alkali Cement P.	
	Series I. % 0·51 Na_2O 0·88 K_2O	Series II. % 0·45 Na_2O 0·81 K_2O	Series I. % 0·00 Na_2O 0·18 K_2O	Series II. % 0·00 Na_2O 0·22 K_2O
Queensland.				
Q. 1. River Sand—Stanley River ..	2	2	2	—3
Q. 2. River Sand—Brisbane River ..	3	2	2	—1
Q. 3. Pit Sand—Brisbane	2	..	2	..
Q. 4. Porphyrite—Mt. Brisbane ..	2	..	2	..
Q. 5. River Gravel—Brisbane River	3	1	2	—2
Q. 6. Porphyry—Brisbane ..	2	0	2	—3
Q. 7. Granite—Grovely	3	1	2	—2
Q. 8. Granite—Ashgrove	3	0	2	—2
Q. 9. Trachyte—Beerburrum ..	..	0	..	—2
Q. 10. Porphyrite—Somerset Dam ..	..	1	..	—1
Q. 11. River Gravel—Mt. Isa ..	..	2	..	—1
New South Wales.				
N. 1. Gravel—Clarencetown ..	3	..	4	..
N. 2. Andesite—Martin's Creek ..	3	2	2	—1
N. 3. Dolerite—Prospect	4	2	2	—2
N. 4. Basalt—near Albion Park ..	4	1	2	—3
N. 5. Slag—Newcastle	4	3	2	1
N. 6. Breccia—Penrith	..	3*	..	0*
Victoria.				
V. 1. Basalt—Fairfield	4	1	2	—1
V. 2. Basalt—North Essendon ..	4	1	1	—1
V. 3. Basalt—Alphington	4	2	2	—1
V. 4. Basalt—Footscray	4	..	1	..
V. 5. Basalt—Brooklyn	3	3	1	—1
V. 6. Basalt—Sunshine	1	2	1	—1
V. 7. Basalt—Tottenham	1	0	1	—1
V. 8. Toscanite—Lilydale	2	1	1	—1
V. 9. Granite—Pyramid Hill ..	5	3	2	—1
V. 10. Washed Sand—Fishermen's Bend	4	0	2	—1
V. 11. Sand—Cranbourne	3	—3	1	—1
V. 12. Sand—Upper Plenty ..	3	—1	1	—3
V. 13. Sand—Cheltenham	3	..	1	..
V. 13A. Sand—Cheltenham	4	..	1	..
V. 14. Sand—Koo-wee-rup	4	0	1	—1
V. 15. Sand—Clayton	..	1	..	—1
V. 16. Scoria—Mt. Noorat	..	5	..	—1
V. 17. Opal—Gippsland	..	188*	..	—1†

* Expansion at twelve months. † Expansion at nine months.

TABLE 1—*continued.*

Aggregate	High-Alkali Cement A.		Low-Alkali Cement P.	
	Series I. % 0·51 Na_2O 0·88 K_2O	Series II. % 0·45 Na_2O 0·81 K_2O	Series I. % 0·00 Na_2O 0·18 K_2O	Series II. % 0·00 Na_2O 0·22 K_2O
Tasmania.				
T. 1. Gravel—Flowerdale	4	4	1	2
T. 2. Dolerite—Near Hobart	3	3	1	1
T. 3. Gravel—Randall's Bay	4	—1	2	1
T. 4. Dolerite—Launceston	3	2	1	..
T. 5. Dolerite—Butler's Gorge	3	2	2	1
T. 6. Quartzite—Butler's Gorge	4	..	2	..
T. 7. Sand—Near Burnie	4	5	2	2
T. 8. Sand—South Arm	15	6	2	—1
T. 9. Sand—Briseis	..	1*	..	—1*
South Australia.				
S. 1. Quartzite—Burnside	3	3	1	—1
S. 2. Sand—Noarlunga	2	1	1	—1
S. 5. Limestone—Near Brighton	3	3	1	—3
S. 6. Sand—Golden Grove	3	2	1	—1
S. 7. Sand—Golden Grove	2	..	1	..
S. 8. Sand—Golden Grove	2	2	2	—1
S. 9. Sand—Golden Grove	4	0	2	—1
S. 10. Sand—Golden Grove	4	1	2	—2
S. 11. Quartzite—Athelstone	1	1	0	—3
S. 12. Quartzite—Mitcham	4	1	1	—1
S. 14. Gravel—Oodnadatta	7	..	2	..
S. 15. Opaline Quartzite—Coober Pedy	31	..	2	..
S. 16. Feldspathic Quartzite—South Para	4	..	2	..
S. 16A. Feldspathic Quartzite—South Para	5	..	2	..
S. 17. Sand—Golden Grove	..	5	..	2
Northern Territory.				
NT. 1. Sandstone—Newcastle Waters	..	1	..	0
NT. 2. Gravel—Tennant's Creek	..	0	..	1
NT. 3. Gravel—Tennant's Creek	..	—1	..	—1
NT. 4. Gravel—Barrow Creek	..	1	..	0
NT. 5. River Gravel—Alice Springs	..	2	..	0
NT. 6. Gravel—Alice Springs	..	2	..	0
NT. 7. River Gravel—Katherine	..	2	..	—1
NT. 8. River Gravel—Mataranka	..	1	..	—1
Non-Australian.				
Z. 1. Sand—Leighton Buzzard, England	5	..	1	..
Z. 2. Siliceous Magnesian Limestone, California, U.S.A.	45*	..	2	..

* Expansion at twelve months.

In Appendix I. each horizontal line shows the composition and average expansion of duplicate mortar bars. Vertical columns give the number and name of each aggregate, the designation and total alkali content of each cement used with that aggregate, and the expansion-behaviour of each mortar resulting from these combinations. The final column gives general comments on the aggregate and the behaviour of the mortars which include it.

The expansion (or in some cases contraction) of each mortar is given at four ages—3, 6, 12, and 24 months. These figures, which are given in hundredths of one per cent., are the average from two bars. In general the two bars of each pair behaved similarly. With low expansions (up to 0·2 per cent.) the variations in percentage expansions of the two bars from their mean rarely exceeded $\pm 0 \cdot 01$ and never $\pm 0 \cdot 02$. With higher expansions (over 0·2 per cent.) greater variations were sometimes shown, but these never exceeded $\pm 0 \cdot 06$. These variations could modify some mean expansions slightly but in no case will they alter them significantly nor will they affect the validity of the conclusions drawn from them. The reasons for these variations in the duplicate bar expansions fall into two categories: (*a*) those due to experimental error caused by chance variations in measurement, in materials, or in storage conditions, and (*b*) those due to changes in the mortar as expansion increases. The former affects all bars but is most obvious in those with low expansion, while the latter affects only those with high expansion which have cracked excessively.

The appearance of damp spots on mortar bars is usually an indication that the aggregate contains some mineral constituent which reacts with the cement. These spots are assumed to be alkali silicate gel (Meissner, 1941) and to be formed by reaction between some siliceous constituent of the aggregate and water-soluble alkali compounds released during hydration of the cement. This is supported by the observation that spots develop more rapidly and are more numerous and larger when high-alkali cement is used than when the cement is low in alkalis. In general the development of spots is also proportional to the expansion of the mortar and indicates that the aggregate should be further examined before use in concrete. However, in the great majority of cases the presence of a few spots is not accompanied by significant expansions nor does the quality of the mortar appear to have deteriorated appreciably.

This examination of mortar bar expansions over a period of 24 months shows that most bars expanded slightly under the conditions of storage (in moist air, in sealed containers, at room temperature). The small but consistent differences between expansions of similar mortars of the first and second series may be due to slight variations in the composition of the cement samples. In some cases the expansion has reached 0·05 per cent. which, in the absence of other signs of reaction, can be regarded as normal. When in the same period expansion exceeds 0·05 per cent. the aggregate or the cement-aggregate combination requires further examination. Expansions of 0·1 per cent. are accompanied by cracking and can be regarded as dangerous.

The expansion records of a number of typical mortars are given in Figs. 1 and 2. When some reactive aggregates are used with low-alkali cements expansion is either negligible or less than when high-alkali cements are used. However, if the aggregate, such as the

siliceous magnesian limestone from California (Z2 in Appendix I.), is very reactive, even low-alkali cements produce expansions which may develop only after one or two years. In such cases it seems that the limitation of alkalis in cement to even a very low figure will not ensure permanent immunity from expansive reaction. At present there seems to be no alternative but to condemn such aggregates for use with any cement.

Mention has been made in an earlier section of this paper of the difficulty of determining the mineral species of cryptocrystalline minerals, particularly those of the silica group. Signs of reactions in mortars are frequently associated with the presence of cryptocrystalline minerals, especially in siliceous rocks.

Petrographic examination of aggregates which contain cryptocrystalline silica should thus be supplemented by mortar tests. Basic cryptocrystalline material, as in basalts, does not usually appear to be similarly reactive, although reaction spots have been noted in basaltic scoria (V16).

In correlating petrographic type with reactivity as aggregate, the present results can lead to useful generalizations for some types of aggregates. The number of samples of other types has been too small for this purpose. The varied origins of natural sands and gravels make such correlation difficult. Of more than thirty aggregates of this type which were examined, half gave no signs of reactivity, somewhat less than half gave slight signs of reactivity, and two or three caused significant though small expansions. These facts suggest that close examination of such materials is desirable. When gravel is of the " gibber " type or occurs in other areas where surface silicification has been active, it should be examined very carefully. This remark applies to all rocks from such regions, as they frequently contain opal or cryptocrystalline silica. Consolidated siliceous sediments such as sandstones and quartzites have characteristics similar to those of unconsolidated sands and gravels and the probability of their being reactive seems to be about the same.

Volcanic or hypabyssal rocks of the acid or intermediate groups (porphyry, trachyte, &c.) should in general be examined carefully. Reactivity of these rocks is associated with the presence of glass. Rocks of these groups (rhyolite, andesite) have also proved to be reactive in other parts of the world. Volcanic and hypabyssal rocks of the basic group which have been examined in this investigation were unweathered and free from secondary silicification. Evidence from these twelve samples would suggest that basalts and dolerites are particularly safe aggregates since none gave any indication of reactivity. It must be remembered, however, that rocks of this type, especially when vesicular, are very subject to a type of silicification in which opal is produced in quantity. Weathering and other secondary changes are major factors in determining the potential reactivity of rock when used as an aggregate. This generalization will apply to most rocks. Only three granites were included in this investigation and although they showed very slight signs of reactivity there seems little evidence to suspect that granite when unweathered is not a safe aggregate.

5. Summary and Conclusions

This work was designed to investigate the possible incidence of expansive reaction in concrete made from Australian materials.

Mortar bars were made from a wide variety of Australian aggregates and cements. Careful observations of these bars for two years disclose that very few aggregates promote significant expansions and although many showed that they contain traces of reactive constituents the great majority can be regarded as safe in this respect. However, the wide geographical distribution and varied petrographic nature of the relatively few dangerous aggregates suggest that aggregates should always be carefully examined before use.

Support is given to published evidence that the presence of opal in aggregates must be regarded as dangerous and that the use of acid and intermediate volcanic rocks must be regarded with suspicion. In Australia, aggregates from the central arid regions, whether rocks *in situ* or unconsolidated sands or gravels, may be dangerous owing to the possible presence of opal. In several rocks cryptocrystalline quartz appeared to cause a dangerous reaction.

Correlation of the behaviour of mortars with the petrographic character of their aggregates suggests that much can be learnt from petrographic study. In many cases this should be sufficient to evaluate an aggregate.

Although the use of low-alkali cement with a reactive aggregate may modify or delay deterioration, the evidence tends to show that such aggregates are undesirable for use with any cement.

6. Acknowledgments

For samples used in this investigation we are indebted to Mr. T. E. Stanton and the California Division of Highways, the South Australian Department of Mines and others too numerous to mention individually.

We are also grateful for the invaluable cooperation and for the financial assistance of the Cement and Concrete Association of Australia.

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APPENDIX I.

Results of Test Bar Observations.

Aggregate.		Cement.		Mean Linear Expansion in Hundredths of 1 Per Cent.				Comment.
Designation.	Type.	Designation.	Percentage Total Alkalis as Na_2O.	3 Months.	6 Months.	12 Months.	24 Months.	
Queensland.								
Q. 1	River Sand, Stanley River. (Quartz feldspar sand)	AI	1·09	0	1	2	2	A few wet spots. No reactive material was identified by petrographic examination
		AII	0·98	0	0	1	2	
		BI	0·89	2	2	3	3	
		CI	0·65	−1	0	1	1	
		CII	0·59	0	1	1	1	
		DI	0·59	0	1	1	1	
		II	0·46	0	2	2	2	
		III	0·46	−6	−4	−3	−3	
		KI	0·41	−2	−1	1	3	
		PI	0·12	0	1	1	2	
		PII	0·15	0	−1	0	−3	
Q. 2	River Sand, Brisbane River. (Quartz sand largely derived from igneous rocks)	AI	1·09	0	1	2	3	Many wet spots. Reaction appears due to cryptocrystalline quartz in some grains. Later measurements show that bars containing this aggregate and high-alkali cement are expanding slowly
		AII	0·98	−1	−1	1	2	
		BI	0·89	1	2	3	4	
		CI	0·65	−1	0	1	2	
		CII	0·59	0	0	1	1	
		DI	0·59	0	1	1	1	
		II	0·46	0	1	2	1	
		III	0·46	0	0	1	0	
		KI	0·41	−1	−1	2	2	
		PI	0·12	1	2	2	2	
		PII	0·15	0	0	1	−1	

APPENDIX I.

Results of Test Bar Observations—*continued.*

Aggregate.		Cement.		Mean Linear Expansion in Hundredths of 1 Per Cent.				Comment.
Designation.	Type.	Designation.	Percentage Total Alkalis as Na_2O.	3 Months.	6 Months.	12 Months.	24 Months.	
Q. 3	Pit Sand, Brisbane. (Quartz sand)	AI	1·09	−1	1	1	2	A few damp spots. No reactive material was identified by petrographic examination
		BI	0·89	1	2	2	3	
		CI	0·65	−1	1	1	1	
		II	0·46	1	2	2	2	
		KI	0·41	−1	0	1	1	
		PI	0·12	1	2	2	2	
Q. 4	Porphyrite, Mt. Brisbane. (Silicified andesite)	AI	1·09	−1	1	1	2	No sign of reaction
		CI	0·65	−1	0	2	2	
		II	0·46	0	1	2	1	
		KI	0·41	−1	0	1	2	
		PI	0·12	0	1	1	2	
Q. 5	River Gravel, Brisbane River. (Quartzite and igneous rock pebbles)	AI	1·09	0	2	2	3	No sign of reaction
		AII	0·98	0	−1	1	1	
		BI	0·89	2	2	2	3	
		CI	0·65	−1	−1	1	1	
		CII	0·59	0	1	1	1	
		DI	0·59	0	1	2	1	
		II	0·46	1	2	2	2	
		III	0·46	0	0	1	1	
		KI	0·41	−1	0	2	2	
		PI	0·12	0	1	1	2	
		PII	0·15	0	0	1	−2	
Q. 6	Porphyry, Brisbane. (Quartz-feldspar-porphyry)	AI	1·09	−1	0	1	2	Many wet spots. Indications of delayed reaction. The rock contains a considerable amount of cryptocrystalline material
		AII	0·98	−1	−2	0	0	
		BI	0·89	1	2	2	3	
		CI	0·65	−2	−1	0	1	
		CII	0·59	−1	−1	−1	1	

Q. 6 *continued* ..	Porphyry, Brisbane. (Quartz-feldspar-porphyry)	DI	0·59	−1	−1	0	−1	Many wet spots. Indications of delayed reaction. The rock contains a considerable amount of cryptocrystalline material
		II	0·46	0	2	2	2	
		III	0·46	−1	−1	5	0	
		JI	0·41	1	2	1	1	
		KI	0·41	−2	−1	0	1	
		PI	0·12	0	1	1	2	
		PII	0·15	−1	−1	−1	−3	
Q. 7	Grey Granite, Grovely ..	AI	1·09	0	2	2	3	Very few damp spots
		AII	0·98	0	0	1	1	
		BI	0·89	2	2	2	3	
		CI	0·65	−1	−1	2	3	
		CII	0·59	0	0	1	1	
		DI	0·59	−1	−1	0	0	
		II	0·46	1	2	2	3	
		III	0·46	0	0	1	1	
		KI	0·41	−1	0	1	2	
		PI	0·12	0	2	2	2	
		PII	0·15	−1	−1	0	−2	
Q. 8	Pink Granite, Ashgrove ..	AI	1·09	0	2	2	3	Very few damp spots
		AII	0·98	−1	−1	1	0	
		BI	0·89	2	3	3	3	
		CI	0·65	−1	−1	1	2	
		CII	0·59	0	0	1	1	
		DI	0·59	0	−1	1	0	
		II	0·46	−1	−2	2	3	
		III	0·46	0	0	0	0	
		KI	0·41	−1	0	1	2	
		PI	0·12	0	2	1	2	
		PII	0·15	−1	−1	0	−2	

APPENDIX I.

Results of Test Bar Observations—*continued.*

Aggregate.		Cement.		Mean Linear Expansion in Hundredths of 1 Per Cent.				Comment.
Designation.	Type.	Designation.	Percentage Total Alkalis as Na_2O.	3 Months.	6 Months.	12 Months.	24 Months.	
Q. 9	Trachyte, Beerburrum ..	AII	0·98	−1	−1	0	0	Many wet spots suggest the possibility of delayed expansion
		CII	0·59	−1	−1	0	0	
		DI	0·59	−2	−2	−1	−1	
		EII	0·48	−2	−1	−1	−1	
		FII	0·47	−2	−2	−1	−1	
		III	0·46	−2	−1	0	−1	
		PII	0·15	−1	−1	0	−2	
Q. 10	Porphyrite, Somerset Dam. (Augite-diorite)	AII	0·98	0	−1	1	1	An occasional damp spot
		CII	0·59	0	0	1	0	
		DI	0·59	−1	−1	0	−1	
		EII	0·48	−1	0	1	0	
		FII	0·47	−1	−1	0	0	
		III	0·46	−2	−1	−1	0	
		PII	0·15	0	−1	0	−1	
Q. 11	River Gravel, Mt. Isa. (Quartz and acid igneous rock pebbles)	AII	0·98	1	1	2	2	A few damp spots
		CII	0·59	0	0	1	1	
		DI	0·59	−1	−1	0	0	
		EII	0·48	0	0	1	0	
		FII	0·47	0	0	1	1	
		III	0·46	0	0	1	0	
		PII	0·15	−1	−1	−1	−1	
New South Wales.								
N. 1	Gravel, Clarencetown. (Arkose pebbles)	AI	1·09	1	2	2	3	No sign of reaction although the aggregate contains much fine siliceous material
		BI	0·89	0	1	3	3	
		CI	0·65	1	2	2	3	
		DI	0·59	1	1	2	3	

N. 1 *continued* ..	Gravel, Clarencetown. (Arkose pebbles)	HI	0·48	1	1	1	2	No sign of reaction although the aggregate contains much fine siliceous material
		II	0·46	−1	−1	1	2	
		KI	0·41	1	1	1	2	
		LI	0·39	0	1	1	2	
		MI	0·30	−1	0	1	2	
		NI	0·26	1	1	1	2	
		OI	0·25	−1	0	1	2	
		PI	0·12	0	2	3	4	
N. 2	Andesite, Martin's Creek ..	AI	1·09	1	1	1	3	No sign of reaction
		AII	0·98	1	2	2	2	
		BI	0·89	0	0	2	3	
		BII	0·89	1	1	2	2	
		CI	0·65	2	3	3	4	
		CII	0·59	0	1	1	1	
		DI	0·59	2	2	2	3	
		DI	0·59	1	1	2	2	
		HI	0·48	2	2	1	3	
		II	0·46	−1	−1	1	2	
		III	0·46	−1	0	0	0	
		KI	0·41	2	2	2	3	
		LI	0·39	0	0	1	1	
		LII	0·37	0	0	1	1	
		MI	0·30	−1	0	0	1	
		MII	0·34	0	1	1	1	
		NI	0·26	−1	0	1	2	
		NII	0·28	0	1	2	2	
		OI	0·25	−1	0	1	2	
		OII	0·30	−1	0	0	0	
		PI	0·12	−1	−1	1	2	
		PII	0·15	−1	−1	0	−1	
N. 3	Dolerite, Prospect	AI	1·09	0	2	3	4	No sign of reaction
		AII	0·98	2	2	3	2	
		BI	0·89	0	1	3	4	
		BII	0·89	1	2	3	3	
		CI	0·65	1	1	2	2	
		CII	0·59	1	1	2	1	
		DI	0·59	−1	1	0	1	

APPENDIX I.

Results of Test Bar Observations—*continued.*

Aggregate.		Cement.		Mean Linear Expansion in Hundredths of 1 Per Cent.				Comment.
Designation.	Type.	Designation.	Percentage Total Alkalis as Na_2O.	3 Months.	6 Months.	12 Months.	24 Months.	
N. 3 *continued* ..	Dolerite, Prospect	DI	0·59	0	0	1	0	No sign of reaction
		FI	0·52	1	2	2	2	
		HI	0·48	−1	1	0	0	
		HI	0·48	−1	−1	0	−1	
		II	0·46	−1	0	1	2	
		III	0·46	0	−1	0	−1	
		KI	0·41	0	1	1	2	
		LI	0·39	−1	0	1	1	
		LII	0·37	0	−1	0	0	
		MI	0·30	−1	0	1	2	
		MII	0·34	−1	−1	−2	−3	
		NI	0·26	−1	0	1	2	
		NII	0·28	1	0	0	−1	
		OI	0·25	−1	0	2	2	
		OII	0·30	0	−1	0	−1	
		PI	0.12	0	0	2	2	
		PII	0.15	−1	−2	−2	−2	
N. 4	Basalt, near Albion Park ..	AI	1·09	2	3	3	4	No sign of reaction
		AII	0·98	1	1	2	1	
		BI	0·89	0	1	3	3	
		BII	0·89	1	1	2	2	
		CI	0·65	1	2	2	2	
		CII	0·59	0	0	1	0	
		DI	0·59	−2	−1	1	1	
		DI	0·59	0	−1	−1	−1	
		HI	0·48	−1	0	−1	0	
		HI	0·48	−1	−2	−1	−3	
		II	0·46	−1	−2	0	1	
		III	0·46	−1	−1	−1	−2	
		KI	0·41	0	1	1	1	

N. 4 *continued* ..	Basalt, near Albion Park ..	LI	0·39	1	1	1	2	No sign of reaction
		LII	0·37	−1	−1	−1	0	
		MI	0·30	1	1	2	2	
		MII	0·34	0	−1	0	−1	
		NI	0·26	1	2	2	2	
		NII	0·28	0	0	0	−1	
		OI	0·25	−2	−1	1	1	
		OII	0·30	0	−1	−1	−2	
		PI	0·12	−1	0	1	2	
		PII	0·15	−2	−2	−2	−3	
N. 5	Blast Furnace Slag, Newcastle	AI	1·09	2	3	3	4	No sign of reaction
		AII	0·98	2	2	3	3	
		BI	0·89	1	2	3	4	
		BII	0·89	2	2	3	3	
		CI	0·65	1	2	3	4	
		CII	0·59	1	1	2	2	
		DI	0·59	2	2	3	4	
		DI	0·59	2	2	3	3	
		HI	0·48	2	2	3	4	
		II	0·46	−1	1	1	3	
		III	0·46	0	1	1	2	
		KI	0·41	1	2	2	4	
		LI	0·39	1	2	2	3	
		LII	0·37	1	1	2	2	
		MI	0·30	−1	1	2	3	
		MII	0·34	1	1	2	3	
		NI	0·26	0	1	2	3	
		NII	0·28	1	1	2	2	
		OI	0·25	−1	1	2	3	
		OII	0·30	0	1	1	1	
		PI	0·12	−1	1	1	2	
		PII	0·15	0	0	1	1	
N. 6	Breccia, Penrith. (Basic volcanic breccia)	AII	0·98	2	3	3	..	No sign of reaction, although the aggregate contains some basic glass
		BII	0·89	3	3	3	..	
		EII	0·48	3	3	4	..	
		PII	0·15	0	0	0	..	

APPENDIX I.

Results of Test Bar Observations—*continued.*

Aggregate.		Cement.		Mean Linear Expansion in Hundredths of 1 Per Cent.				Comment.
Designation.	Type.	Designation.	Percentage Total Alkalis as Na_2O.	3 Months.	6 Months.	12 Months.	24 Months.	
Victoria.								
V. 1	Basalt, Fairfield	AI	1·09	1	2	2	4	No sign of reaction
		AII	0·98	0	0	1	1	
		FI	0·52	−1	1	1	2	
		FII	0·47	−1	−1	0	−1	
		JI	0·41	1	2	3	..	
		PI	0·12	0	1	2	2	
		PII	0·15	0	0	1	−1	
V. 2	Basalt, North Essendon ..	AI	1·09	1	2	3	4	No sign of reaction
		AII	0·98	1	1	1	1	
		FI	0·52	−1	1	1	1	
		FII	0·47	−2	−2	−1	−2	
		JI	0·41	1	2	2	3	
		PI	0·12	0	1	1	1	
		PII	0·15	0	0	0	−1	
V. 3	Basalt, Alphington ..	AI	1·09	1	2	3	4	No sign of reaction
		AII	0·98	1	1	1	2	
		FI	0·52	−1	1	1	1	
		FII	0·47	−1	−1	0	−1	
		JI	0·41	1	2	2	3	
		PI	0·12	0	1	1	2	
		PII	0·15	0	0	1	−1	

V. 4	Basalt, Footscray	AI	1·09	1	3	3	4	No sign of reaction
		FI	0·52	0	1	2	2	
		JI	0·41	1	2	2	3	
		PI	0·12	0	1	1	1	
V. 5	Basalt, Brooklyn	AI	1·09	−1	1	2	3	No sign of reaction
		AII	0·98	1	1	2	3	
		FI	0·52	0	2	2	2	
		FII	0·47	0	1	1	1	
		JI	0·41	1	2	2	3	
		PI	0·12	0	1	0	1	
		PII	0·15	0	−1	0	−1	
V. 6	Basalt, Sunshine	AI	1·09	−1	0	0	1	No sign of reaction
		AII	0·98	1	1	2	2	
		FI	0·52	0	1	1	2	
		FII	0·47	0	0	1	1	
		JI	0·41	0	2	1	2	
		PI	0·12	0	0	−1	1	
		PII	0·15	0	−1	0	−1	
V. 7	Basalt, Tottenham	AI	1·09	−1	0	1	1	No sign of reaction
		AII	0·98	0	−1	0	0	
		FI	0·52	0	1	1	2	
		FII	0·47	0	0	0	0	
		JI	0·41	0	2	2	2	
		PI	0·12	0	2	0	1	
		PII	0·15	−1	−1	0	−1	

APPENDIX I.

Results of Test Bar Observations—*continued.*

Aggregate.		Cement.		Mean Linear Expansion in Hundredths of 1 Per Cent.				Comment.
Designation.	Type.	Designation.	Percentage Total Alkalis as Na_2O.	3 Months.	6 Months.	12 Months.	24 Months.	
V. 8	Toscanite, Lilydale	AI	1·09	0	1	1	2	No sign of reaction
		AII	0·98	3	3	3	1	
		BI	0·89	2	3	3	3	
		CI	0·65	1	2	2	3	
		CII	0·59	0	0	2	0	
		DI	0·59	−2	−2	0	−1	
		EI	0·57	1	2	2	2	
		EII	0·48	−1	−2	0	−1	
		FI	0·52	0	2	2	2	
		FII	0·47	−4	−3	−3	−3	
		GII	0·52	0	0	1	1	
		II	0·46	0	1	1	1	
		JI	0·41	1	3	3	3	
		KI	0·41	1	2	2	2	
		OI	0·25	0	1	1	2	
		PI	0·12	0	0	0	1	
		PII	0·15	0	−1	0	−1	
V. 9	Granite, Pyramid Hill, near Kerang. (Adamellite)	AI	1·09	2	3	4	5	Very few damp spots
		AII	0·98	2	2	2	3	
		BI	0·89	2	2	3	3	
		CII	0·59	0	0	2	2	
		DI	0·59	−1	−1	1	0	
		EII	0·48	0	−1	1	0	
		FI	0·52	1	2	2	3	
		FII	0·47	−3	−2	−1	−1	
		GII	0·52	1	0	2	2	
		PI	0·12	0	2	2	2	
		PII	0·15	0	0	1	−1	

V. 10	Washed Sand, Fishermen's Bend. (Quartz Sand) ..	AI	1·09	1	2	3	4	No sign of reaction
		AII	0·98	1	1	1	0	
		FI	0·52	0	1	3	2	
		FII	0·47	−2	−1	0	−1	
		JI	0·41	1	3	4	5	
		PI	0·12	0	1	2	2	
		PII	0·15	0	0	1	−1	
V. 11	Sand, Cranbourne. (Quartz Sand)	AI	1·09	0	1	2	3	No sign of reaction
		AII	0·98	0	−1	−1	−3	
		FI	0·52	−1	1	2	3	
		FII	0·47	−1	−1	0	0	
		JI	0·41	1	2	3	4	
		PI	0·12	0	0	1	1	
		PII	0·15	0	0	1	−1	
V. 12	Sand, Upper Plenty. (Quartz Sand)	AI	1·09	0	1	2	3	No sign of reaction
		AII	0·98	0	0	0	−1	
		FI	0·52	−1	1	2	2	
		FII	0·47	0	0	0	0	
		JI	0·41	1	2	3	4	
		PI	0·12	0	1	1	1	
		PII	0·15	−2	−2	−1	−3	
V. 13	Sand, Cheltenham. (Quartz Sand)	AI	1·09	−1	1	2	3	No sign of reaction
		FI	0·52	−1	1	1	2	
		JI	0·41	1	2	3	4	
		PI	0·12	0	1	1	1	

APPENDIX I.

Results of Test Bar Observations—*continued.*

Aggregate.		Cement.		Mean Linear Expansion in Hundredths of 1 Per Cent.				Comment.
Designation.	Type.	Designation.	Percentage Total Alkalis as Na_2O.	3 Months.	6 Months.	12 Months.	24 Months.	
V. 13A	Sand, Cheltenham. (Quartz sand)	AI	1·09	0	1	3	4	No sign of reaction
		FI	0·52	0	2	2	3	
		JI	0·41	2	3	4	4	
		PI	0·12	−1	0	1	1	
V. 14	Sand, Koo-wee-rup. (Quartz sand)	AI	1·09	0	1	3	4	No sign of reaction
		AII	0·98	0	0	1	0	
		FI	0·52	1	2	2	3	
		FII	0·47	0	−1	0	0	
		JI	0·41	2	3	4	4	
		PI	0·12	1	1	1	1	
		PII	0·15	−1	0	1	−1	
V. 15	Sand, Clayton. (Quartz sand)	AII	0·98	1	1	2	1	No sign of reaction
		FII	0·47	−1	0	0	0	
		PII	0·15	0	0	1	−1	
V. 16	Scoria, Mt. Noorat, Terang District	AII	0·98	0	0	1	5	Few wet spots. This aggregate gives a porous mortar which would probably not expand, although reaction takes place. Presence of basic glass may cause reaction
		CII	0·59	0	0	1	1	
		DI	0·59	0	0	−4	−5	
		EII	0·48	0	0	1	0	
		FII	0·47	−1	−1	0	−1	
		GII	0·52	0	0	1	0	
		PII	0·15	−1	−1	−1	−1	

V. 17*	Opal, Butcher's Ridge, East Gippsland	AII PII	0·98 0·15	81 −1	128 −1	188 ..	.. ..	Numerous wet spots. A dangerous aggregate
Tasmania.								
T. 1	Gravel, Flowerdale. (Quartzite gravel)	AI AII FI FII JI PI PII	1·09 0·98 0·52 0·47 0·41 0·12 0·15	1 0 1 0 2 0 −1	3 1 1 1 1 1 0	3 1 2 0 1 1 0	4 3 3 1 2 1 1	No sign of reaction, although the aggregate contains some fine siliceous material
T. 2	Dolerite, 20 miles north of Hobart	AI AII FI FII JI PI PII	1·09 0·98 0·52 0·47 0·41 0·12 0·15	1 −1 0 0 1 −1 −1	3 0 1 0 1 1 −1	3 0 2 1 0 1 0	3 3 3 −1 1 1 1	No sign of reaction
T. 3	Gravel, Randall's Bay. (Quartz gravel)	AI AII FI FII JI PI PII	1·09 0·98 0·52 0·47 0·41 0·12 0·15	1 0 2 0 2 0 −1	2 1 2 1 2 1 0	3 1 2 1 1 1 0	4 −1 3 0 2 2 1	A few wet spots. Petrographic examination did not reveal reactive material

* Mixed with 95 per cent. Leighton Buzzard sand (Z. 1).

APPENDIX I.

Results of Test Bar Observations—*continued.*

Aggregate.		Cement.		Mean Linear Expansion in Hundredths of 1 Per Cent.				Comment.
Designation.	Type.	Designation.	Percentage Total Alkalis as Na_2O.	3 Months.	6 Months.	12 Months.	24 Months.	
T. 4	Dolerite, Launceston ..	AI	1·09	1	2	2	3	No sign of reaction
		AII	0·98	0	1	1	2	
		FI	0·52	1	2	2	2	
		FII	0·47	0	1	0	—1	
		JI	0·41	1	2	2	2	
		PI	0·12	0	1	0	1	
T. 5	Dolerite, Butler's Gorge ..	AI	1·09	0	1	2	3	No sign of reaction
		AII	0·98	—1	0	0	2	
		FI	0·52	1	2	2	2	
		FII	0·47	0	0	0	0	
		JI	0·41	1	2	2	2	
		PI	0·12	0	1	1	2	
		PII	0·15	—1	0	1	1	
T. 6	Quartzite Sand, Butler's Gorge	AI	1·09	1	2	3	4	No sign of reaction, although the aggregate contains some fine-grained siliceous material
		FI	0·52	2	2	2	3	
		JI	0·41	2	2	2	3	
		PI	0·12	0	1	1	2	

T. 7	Sand, near Burnie. (Quartz sand)	AI	1·09	0	1	3	4	A few wet spots. This aggregate contains some cryptocrystalline quartz
		AII	0·98	2	3	3	5	
		FI	0·52	1	2	2	3	
		FII	0·47	0	1	2	3	
		JI	0·41	2	3	3	4	
		PI	0·12	0	1	2	2	
		PII	0·15	−1	0	0	2	
T. 8	Sand, South Arm, Derwent River. (Quartz sand)	AI	1·09	0	2	4	15	Very many wet spots. Shows delayed expansion. Dangerous with high-alkali cements and as expansion is increasing it may prove dangerous with medium- and low-alkali cements. Reaction probably due to cryptocrystalline quartz
		AII	0·98	1	2	3	6	
		CII	0·59	0	0	1	0	
		DI	0·59	0	0	1	1	
		EII	0·48	0	0	1	1	
		FI	0·52	1	2	3	4	
		FII	0·47	0	1	1	0	
		GII	0·52	0	1	1	1	
		JI	0·41	2	3	3	4	
		PI	0·12	0	1	2	2	
		PII	0·15	−1	0	1	−1	
T. 9	Sand, Briseis. (Quartz topaz sand)	AII	0·98	1	1	1	..	No sign of reaction
		PII	0·15	−1	−1	−1	..	
South Australia.								
S. 1	Quartzite, Burnside ..	AI	1·09	2	3	3	3	A few wet spots. Reaction may be due to cryptocrystalline quartz or altered feldspar
		AII	0·98	0	1	1	3	
		BI	0·89	2	2	3	3	
		EI	0·57	1	1	2	2	
		EII	0·48	1	1	1	1	
		GII	0·52	1	2	2	2	
		JI	0·41	1	2	3	2	
		PI	0·12	0	1	1	1	
		PII	0·15	0	0	1	−1	

APPENDIX I.

Results of Test Bar Observations—*continued.*

Aggregate.		Cement.		Mean Linear Expansion in Hundredths of 1 Per Cent.				Comment.
Designation.	Type.	Designation.	Percentage Total Alkalis as Na_2O.	3 Months.	6 Months.	12 Months.	24 Months.	
S. 2	Sand, Noarlunga. (Quartz sand)	AI	1·09	0	1	2	2	A very few wet spots
		AII	0·98	1	0	1	1	
		EI	0·57	2	3	3	4	
		EII	0·48	1	1	1	1	
		GII	0·52	1	1	2	1	
		JI	0·41	1	2	3	2	
		PI	0·12	1	1	−1	1	
		PII	0·15	−1	−1	1	−1	
S. 5	Limestone, near Brighton ..	AI	1·09	1	2	2	3	A very few damp spots
		AII	0·98	−1	−3	0	3	
		BI	0·89	1	1	1	1	
		EI	0·57	0	1	1	2	
		EII	0·48	−1	−1	−1	−1	
		GII	0·52	0	−1	0	0	
		PI	0·12	−1	1	1	1	
		PII	0·15	−1	−2	0	−3	
S. 6	Sand, Golden Grove. (Quartz sand)	AI	1·09	−1	1	2	3	No sign of reaction
		AII	0·98	1	1	1	2	
		EI	0·57	2	3	3	4	
		EII	0·48	0	−1	−1	0	
		GII	0·52	1	1	1	1	
		JI	0·41	1	2	3	2	
		PI	0·12	1	1	1	1	
		PII	0·15	0	−1	1	−1	

S. 7	Sand, Golden Grove. (Quartz sand)	AI	1·09	0	1	2	2	A few damp spots No reactive material was identified by petrographic examination
		BI	0·89	2	2	2	2	
		EI	0·57	1	3	3	4	
		JI	0·41	1	2	3	2	
		PI	0·12	1	1	1	1	
S. 8	Sand, Golden Grove. (Quartz sand)	AI	1·09	0	1	2	2	A few damp spots. (Similar to S. 7)
		AII	0·98	1	1	1	2	
		EI	0·57	1	3	3	4	
		EII	0·48	−1	−1	−1	−1	
		GII	0·52	0	0	0	0	
		JI	0·41	1	2	3	3	
		PI	0·12	0	1	2	2	
		PII	0·15	−1	−1	1	−1	
S. 9	Sand, Golden Grove. (Quartz sand)	AI	1·09	2	2	3	4	A few wet spots. (Similar to S. 7)
		AII	0·98	1	0	0	0	
		EI	0·57	1	2	3	4	
		EII	0·48	0	−1	−2	0	
		GII	0·52	0	0	0	0	
		JI	0·41	1	2	3	3	
		PI	0·12	0	1	1	2	
		PII	0·15	0	−1	1	−1	
S. 10	Sand, Golden Grove. (Quartz sand)	AI	1·09	2	2	3	4	No sign of reaction
		AII	0·98	1	0	1	1	
		BI	0·89	2	2	3	3	
		EI	0·57	1	3	3	4	
		EII	0·48	−1	−1	0	1	
		GII	0·52	0	0	2	2	
		JI	0·41	1	2	2	3	
		PI	0·12	0	1	1	2	
		PII	0·15	−1	−1	0	−2	

APPENDIX I.

Results of Test Bar Observations—*continued.*

Aggregate.		Cement.		Mean Linear Expansion in Hundredths of 1 Per Cent.				Comment.
Designation.	Type.	Designation.	Percentage Total Alkalis as Na_2O.	3 Months.	6 Months.	12 Months.	24 Months.	
S. 11	Quartzite, Athelstone ..	AI	1·09	0	1	1	1	An occasional damp spot
		AII	0·98	0	−1	−1	1	
		BI	0·89	1	2	2	2	
		EI	0·57	1	2	3	3	
		EII	0·48	0	−2	−1	−1	
		GII	0·52	0	−1	1	1	
		JI	0·41	0	1	2	2	
		PI	0·12	−1	−1	0	0	
		PII	0·15	−1	−2	0	−3	
S. 12	Quartzite, Mitcham	AI	1·09	1	3	4	4	A few damp spots. Contains 0·1 per cent. opal
		AII	0·98	0	−1	−1	1	
		BI	0·89	2	3	3	3	
		EI	0·57	1	2	3	4	
		EII	0·48	−1	−2	−1	0	
		GII	0·52	−1	−1	1	2	
		PI	0·12	−1	0	1	1	
		PII	0·15	0	0	0	−1	
S. 14	Surface Gravel, Oodnadatta ..	AI	1·09	3	6	7	8	Numerous wet spots. Regarded as an unsatisfactory aggregate. Reaction due to opal
		AI	1·09	2	4	5	6	
		BI	0·89	2	4	5	6	
		CI	0·65	1	2	3	4	
		DI	0·59	1	3	4	4	
		EI	0·57	2	4	5	7	

S. 14 *continued* ..	Surface Gravel, Oodnadatta ..	EI	0·57	1	3	4	4	Numerous wet spots. Regarded as an unsatisfactory aggregate. Reaction due to opal
		FI	0·52	1	3	3	4	
		HI	0·48	0	3	3	3	
		II	0·46	1	2	2	3	
		JI	0·41	2	4	5	7	
		KI	0·41	0	2	2	3	
		LI	0·39	1	2	1	2	
		MI	0·30	1	2	2	3	
		NI	0·26	1	2	2	3	
		OI	0·25	0	1	1	3	
		PI	0·12	0	1	2	2	
		PI	0·12	0	1	1	2	
S. 15	Opaline Quartzite, Coober Pedy	AI	1·09	15	20	26	31	Numerous wet spots. A dangerous aggregate, which contains opal
		EI	0·57	2	3	6	10	
		PI	0·12	1	2	2	2	
S. 16	Feldspathic Quartzite, South Para	AI	1·09	3	3	4	4	No sign of reaction
		EI	0·57	2	2	2	3	
		PI	0·12	2	1	1	2	
S. 16A	Feldspathic Quartzite, South Para	AI	1·09	3	3	4	5	No sign of reaction
		EI	0·57	2	2	2	3	
		PI	0·12	2	2	2	2	
S. 17	Sand, Golden Grove. (Quartz sand)	AII	0·98	−3	−1	−1	5	No sign of reaction
		EII	0·48	−1	−1	0	1	
		GII	0·52	1	0	2	3	
		PII	0·15	−1	1	1	2	

APPENDIX I.

Results of Test Bar Observations—*continued.*

Aggregate.		Cement.		Mean Linear Expansion in Hundredths of 1 Per Cent.				Comment.
Designation.	Type.	Designation.	Percentage Total Alkalis as Na_2O.	3 Months.	6 Months.	12 Months.	24 Months.	
Northern Territory.								
NT. 1	Sandstone, Newcastle Waters	AII	0·98	0	0	1	1	An occasional damp spot
		CII	0·59	0	1	1	0	
		EII	0·48	−2	−2	−1	−2	
		PII	0·15	0	0	1	0	
NT. 2	Gravel, Tennant's Creek. (Ferruginous sandstone gravel)	AII	0·98	0	0	1	0	Very few damp spots
		CII	0·59	0	0	1	0	
		EII	0·48	−3	−2	−1	−2	
		PII	0·15	0	1	1	1	
NT. 3	Gravel, Tennant's Creek. (Sandstone gravel)	AII	0·98	−1	−1	0	−1	Many wet spots. This rock contains a little cryptocrystalline quartz
		CII	0·59	0	0	1	0	
		EII	0·48	−3	−2	−1	−2	
		PII	0·15	0	0	0	−1	
NT. 4	Gravel, Barrow Creek. (Quartzite, sandstone and trachyte pebbles)	AII	0·98	0	1	1	1	No sign of reaction, although this rock contains some fine-grained siliceous material
		CII	0·59	0	1	1	1	
		EII	0·48	−3	−2	−2	−2	
		PII	0·15	0	0	1	0	
NT. 5	River Gravel, Alice Springs. (Granite and gneiss gravel)	AII	0·98	1	1	2	2	An occasional damp spot
		CII	0·59	0	1	2	1	
		EII	0·48	−2	−1	0	−1	
		PII	0·15	0	0	0	0	

NT. 6	Gravel, Alice Springs. (Feldspathic quartzite gravel)	AII	0·98	1	1	2	2	A few damp spots. Contains both fine-grained siliceous material and extensively altered feldspar
		CII	0·59	0	1	2	0	
		EII	0·48	0	0	1	1	
		PII	0·15	−1	−1	0	0	
NT. 7	River Gravel, Katherine. (Quartzite chalcedonic rock gravel)	AII	0·98	1	1	2	2	Many wet spots. Presence of much cryptocrystalline quartz suggests the possibility of delayed expansion
		CII	0·59	0	0	1	0	
		EII	0·48	0	−1	0	0	
		PII	0·15	−2	−2	−1	−1	
NT. 8	River Gravel, Mataranka. (Quartzite and sandstone gravel)	AII	0·98	1	1	2	1	Many wet spots. Presence of much crypotcrystalline quartz suggests the possibility of delayed expansion
		CII	0·59	0	0	1	−1	
		EII	0·48	−1	−1	0	−1	
		PII	0·15	−2	−2	−1	−1	
Non-Australian.								
Z. 1	Sand, Leighton Buzzard, England. (Standard quartz sand)	AI	1·09	2	3	4	5	No sign of reaction
		BI	0·89	1	3	4	5	
		CI	0·65	−1	0	1	3	
		DI	0·59	1	2	2	1	
		EI	0·57	1	2	3	3	
		FI	0·52	0	1	2	3	
		HI	0·48	1	2	2	1	
		II	0·46	0	1	1	2	
		JI	0·41	1	2	3	4	

APPENDIX I.

Results of Test Bar Observations—*continued.*

Aggregate.		Cement.		Mean Linear Expansion in Hundredths of 1 Per Cent.				Comment.
Designation.	Type.	Designation.	Percentage Total Alkalis as Na_2O.	3 Months.	6 Months.	12 Months.	24 Months.	
Z. 1 *continued* ..	Sand, Leighton Buzzard, England. (Standard quartz sand)	KI	0·41	−1	0	1	2	No sign of reaction
		LI	0·39	−1	0	1	2	
		MI	0·30	0	1	1	2	
		NI	0·26	1	2	3	3	
		OI	0·25	0	1	2	2	
		PI	0·12	−1	0	1	1	
Z. 2	Siliceous Magnesian Limestone, California, U.S.A. (Mixed with 90 per cent. Leighton Buzzard sand)	AI	1·09	9	10	11	13*	Numerous wet spots. Reaction due to opal. A known reactive aggregate
		AI	1·09	44	45	45	..	
		BI	0·89	46	51	53	54	
		CI	0·65	20	42	51	56	
		DI	0·59	67	103	139	..	
		EI	0·57	33	40	42	43	
		FI	0·52	38	52	53	57	
		HI	0·48	5	17	22	29	
		II	0·46	16	28	37	43	
		JI	0·41	22	41	68	73	
		KI	0·41	7	24	33	37	
		LI	0·37	1	3	9	35	
		MI	0·30	0	2	3	5	
		NI	0·26	1	3	5	30	
		OI	0·25	1	4	8	30	
		PI	0·12	−1	0	1	2	

* The expansion of this mortar appeared anomalous. The check test showed that it expanded as expected.

APPENDIX II.

Percentage Composition of Cements.

Cement.	SiO_2.	Fe_2O_3.	Al_2O_3.	CaO.	MgO.	SO_3.	Loss on Ignition.	Na_2O.	K_2O.	Total Alkalis.*
AI ..	21·86	2·38	5·00	63·84	1·18	1·99	1·84	0·51	0·88	1·09
AII ..	22·14	2·38	4·94	64·12	1·08	1·84	1·88	0·45	0·81	0·98
BI ..	21·85	2·17	6·46	63·61	0·69	2·19	2·05	0·59	0·45	0·89
BII ..	21·06	2·85	5·67	63·96	0·70	2·18	2·47	0·59	0·45	0·89
CI ..	21·14	2·79	5·97	64·08	1·53	1·93	1·48	0·59	0·09	0·65
CII ..	21·56	3·37	5·63	63·96	1·43	1·88	1·16	0·50	0·14	0·59
DI ..	21·62	2·78	6·44	63·88	1·14	1·37	1·61	0·15	0·67	0·59
EI ..	21·98	3·42	4·62	63·18	1·86	2·56	1·46	0·17	0·60	0·57
EII ..	21·88	3·15	4·35	64·00	1·78	1·83	1·93	0·09	0·59	0·48
FI ..	21·81	2·78	5·73	63·82	1·30	1·96	1·85	0·05	0·72	0·52
FII ..	21·78	2·86	5·98	63·98	1·33	1·75	1·51	0·00	0·71	0·47
GII ..	22·20	3·57	4·43	61·98	2·35	2·02	2·40	0·12	0·60	0·52
HI ..	22·80	6·06	4·88	61·90	0·72	1·61	1·30	0·04	0·67	0·48
II ..	21·84	2·34	6·14	64·08	1·37	1·69	1·56	0·00	0·70	0·46
III ..	21·98	1·85	6·03	64·00	1·45	1·67	2·17	0·00	0·70	0·46
JI ..	21·66	5·14	5·05	62·92	1·17	1·58	1·65	0·00	0·62	0·41
KI ..	23·46	3·86	4·48	63·40	1·27	1·69	1·19	0·41	0·00	0·41
LI ..	23·14	5·06	4·74	63·12	0·54	1·39	1·25	0·04	0·53	0·39
LII ..	23·22	5·20	4·06	62·86	0·41	1·37	2·24	0·00	0·56	0·37
MI ..	21·20	1·94	6·04	64·98	1·83	1·64	1·59	0·00	0·45	0·30
MII ..	21·54	2·05	4·89	65·12	1·81	1·96	2·05	0·00	0·52	0·34
NI ..	23·98	4·37	3·32	62·35	1·60	1·90	1·69	0·00	0·39	0·26
NII ..	23·88	4·56	3·50	61·48	1·53	1·68	2·73	0·00	0·42	0·28
OI ..	21·23	3·44	7·31	63·70	0·62	1·82	0·99	0·00	0·38	0·25
OII ..	21·22	2·75	7·15	63·62	0·50	1·92	2·38	0·00	0·46	0·30
PI ..	23·42	5·33	4·33	61·90	0·74	1·85	2·05	0·00	0·18	0·12
PII ..	23·56	5·17	4·25	61·64	0·61	1·57	2·89	0·00	0·22	0·15

* $Na_2O + 0{\cdot}658\ K_2O$.

All analyses by H. T. Philippe.

APPENDIX III.

Petrographic Descriptions of Aggregates.

QUEENSLAND.

Q.1. *River Sand, Stanley River.*

Quartz-feldspar sand containing about 25 per cent. feldspar (orthoclase and plagioclase) most of which is only slightly kaolinized. Some limonitic grains are present. The grains are angular to sub-angular.

Q.2. *River Sand, Brisbane River.*

Quartz sand with a large amount of quartzite, feldspar, and igneous rock grains.

Quartzite: Very fine-grained, partly cryptocrystalline, coloured with limonite or chlorite.

Feldspar: Orthoclase and plagioclase, mostly fresh.

Igneous rock: Appears to be strongly silicified porphyry consisting of quartz, feldspar, hornblende, and much chlorite.

The grains are sub-angular.

Q.3. *Pit Sand, Brisbane.*

Quartz sand containing some limonitic grains. The grains are sub-angular to rounded.

Q.4. *Porphyrite, Mt. Brisbane.*

Metamorphosed porphyritic rock, probably andesite, containing primary and secondary quartz, primary and secondary feldspar (mainly plagioclase, some orthoclase), epidote, biotite, chlorite, and augite. Opal less than 0·01 per cent.

Q.5. *River Gravel, Brisbane River.*

Pebbles of quartzite and igneous rock.

Quartzite: Consists almost entirely of quartz with a little limonite.

Igneous rock: Includes both porphyries and plutonic rocks all exceedingly altered. The main minerals are extremely altered feldspar, quartz, and chlorite.

Q.6. *Porphyry, Brisbane.*

Metamorphosed quartz-feldspar-porphyry containing porphyritic quartz and feldspar (mostly orthoclase) in a microcrystalline and cryptocrystalline groundmass of quartz, altered feldspar, chlorite, and hematite. Opal less than 0·1 per cent.

Q.7. *Grey Granite, Grovely.*

Medium-grained granite consisting of partly kaolinized orthoclase, quartz, chloritized biotite, and a little ilmenite.

Q.8. *Pink Granite, Ashgrove.*

Fine-grained granite with small porphyritic quartz crystals. Consists of kaolinized orthoclase, quartz, plagioclase, and chloritized biotite with some secondary calcite and sericite. Opal less than 0·01 per cent.

Q.9. *Trachyte, Beerburrum.*

Light-grey spotted trachyte consisting of quartz in a groundmass of altered feldspar (mostly orthoclase) with some hornblende and chlorite. In spite of the alteration of the feldspar the rock is very dense.

Q.10. *Porphyrite, Somerset Dam.*

Grey augite diorite consisting of feldspar (mostly plagioclase, some orthoclase) and augite with biotite, quartz, and ilmenite. Both the augite and biotite show alteration to chlorite.

Q.11. *River Gravel, Mt. Isa.*

Reddish gravel consisting of quartz, quartzite, and acid igneous rock pebbles.

Quartzite: Contains some bleached biotite flakes and has interstitial hematite, limonite and clay material. Some pebbles are very rich in hematite.

Igneous rock: Very fresh feldspar porphyry Plagioclase phenocrysts in a fine-grained quartz-feldspar (probably plagioclase) groundmass with hornblende, ilmenite, epidote, garnet, and a little apatite.

New South Wales.

N.1. *Gravel, Clarencetown.*

Pebbles of arkose and sandstone.

Arkose: Fine quartz, plagioclase feldspar and magnetite in a microcrystalline ferruginous and siliceous cement with very fine chlorite and epidote. Some isotropic material is present.

Sandstone: Similar rock without feldspar.

N.2. *Andesite, Martin's Creek.*

Reddish-grey porphyritic andesite consisting of partly kaolinized plagioclase phenocrysts in a medium- to fine-grained groundmass of limonite-stained kaolinized feldspar, with some ilmenite, hornblende, and chloritized biotite. Some cryptocrystalline material is present.

N.3. *Dolerite, Prospect.*

Dark-grey coarse-grained dolerite consisting of slightly kaolinized plagioclase feldspar, completely serpentinized olivine and augite, with some ilmenite, biotite, zeolites, and calcite.

N.4. *Basalt, near Albion Park.*

Dark-grey basalt with occasional phenocrysts of plagioclase feldspar, augite, and olivine, completely converted to iddingsite, in a groundmass of feldspar laths, augite, ilmenite, and iddingsite.

N.5. *Blast Furnace Slag, Newcastle.*

Grey, green, and black slag; some compact and some vesicular. Contains crystals and crystallites of iron akermanite in a glassy base.

N.6. *Breccia, Penrith.*

Hard, grey, fine-grained breccia consisting of fragments of glassy basic volcanic rock, slate, and quartz with considerable secondary calcite and some chlorite.

Victoria.

V.1. *Basalt, Fairfield.*

V.2. *Basalt, North Essendon.*

V.3. *Basalt, Alphington.*

V.4. *Basalt, Footscray.*

V.5. *Basalt, Brooklyn.*

V.6. *Basalt, Sunshine.*

V.7. *Basalt, Tottenham.*

These rocks are all very similar. Grey basalts consisting of fresh plagioclase feldspar, augite, olivine, partly to completely iddingsitized or serpentinized, and ilmenite with some interstitial cryptocrystalline material. Some are vesicular with cavities filled with serpentine, calcite, and zeolites.

V.8. *Toscanite, Lilydale.*

Very fine-grained grey toscanite consisting of kaolinized feldspar, quartz, chloritized biotite, ilmenite, and hematite.

V.9. *Granite, Pyramid Hill, near Kerang.*

Medium- to coarse-grained light-grey adamellite consisting of quartz, orthoclase and plagioclase feldspar, biotite (chloritized in places), and muscovite. The feldspar is quite unaltered.

V.10. *Washed Sand, Fishermen's Bend.*

Clean quartz sand. The grains are sub-angular to rounded.

V.11. *Sand, Cranbourne.*

Yellow-brown quartz sand containing some ilmenite. The grains are sub-angular.

V.12. *Sand, Upper Plenty.*

Brownish quartz sand containing some ilmenite. The grains are sub-angular.

VICTORIA—*continued.*

V.13. and 13A. *Sand, Cheltenham.*

Very fine brownish quartz sand with a little ilmenite. The grains are rounded. Cryptocrystalline silica 0·1 to 0·2 per cent.

V.14. *Sand, Koo-wee-rup.*

Clean quartz sand with some feldspar. The grains are angular.

V.15. *Sand, Clayton.*

White quartz sand with a few limonite-stained grains, muscovite flakes, and a little clayey material. The grains are rounded.

V.16. *Scoria, Mt. Noorat, Terang District.*

Basaltic scoria with olivine and a little augite in a brown glass varying from clear to opaque owing to development of microlites.

V.17. *Opal, Butcher's Ridge, East Gippsland.*

Milky-white to brown common opal occurring as veins in basalt. Chiefly opal but chalcedony is plentiful in cracks and vughs. A little quartz and limonite are also present.

TASMANIA.

T.1. *Gravel, Flowerdale.*

White quartzite gravel, the quartzite consisting almost entirely of quartz grains with interstitial fine quartz, cryptocrystalline in places.

T.2. *Dolerite, 20 miles north of Hobart.*

Grey dolerite with augite slightly altered to chlorite, in a medium-grained groundmass of plagioclase feldspar laths and ilmenite with interstitial cryptocrystalline material and a little calcite.

T.3. *Gravel, Randall's Bay, 30 miles south of Hobart.*

White gravel consisting of quartz and coarse-grained quartzite pebbles.

T.4. *Dolerite, Launceston.*

Grey dolerite with augite slightly altered to chlorite in a medium-grained groundmass of fresh plagioclase feldspar laths and ilmenite with interstitial cryptocrystalline material.

T.5. *Dolerite, Butler's Gorge.*

Grey dolerite with augite phenocrysts in a medium-grained groundmass of fresh plagioclase feldspar laths and ilmenite with interstitial cryptocrystalline material.

T.6. *Quartzite Sand, Butler's Gorge.*

Crushed quartzite consisting of quartz grains with interstitial fine-grained quartz with some hematite, sericite, and chlorite. Some calcite veins are present.

T.7. *Sand, near Burnie.*

Fine quartz sand consisting of angular quartz grains with up to 5 per cent. of grains of cryptocrystalline quartz.

T.8. *Sand, South Arm, Derwent River.*

White quartz sand containing about 15 per cent. of grains of cryptocrystalline quartz.

T.9. *Sand, Briseis.*

Quartz sand with a few limonite-stained grains, a little slaty material, a little feldspar, and a considerable amount of topaz.

SOUTH AUSTRALIA.

S.1. and 1A. *Quartzite, Burnside.*

Medium-grained quartzite consisting of granoblastic quartz with some orthoclase feldspar slightly kaolinized and some interstitial fine quartz and muscovite. Opal less than 0·05 per cent.

S.2. *Sand, Noarlunga.*

Quartz sand with some clay and carbonaceous material. The grains are rounded to sub-angular.

South Australia—*continued.*

S.5. *Limestone, near Brighton.*

Fine-grained blue and reddish limestone containing considerable quartz and ferruginous material with some feldspar and muscovite, and veins of calcite. Opal approximately 0·1 per cent.

S.6. *Sand, Golden Grove.*

S.7. *Sand, Golden Grove.*

S.8. *Sand, Golden Grove.*

S.9. *Sand, Golden Grove.*

S.10. *Sand, Golden Grove.*

These sands are all very similar, yellow to reddish quartz sand of sub-angular limonite-stained quartz grains, varying only in accessory minerals which are as follows:—

S.6.—Feldspar.

S.7.—Muscovite, bleached biotite, tourmaline, ilmenite, epidote, zircon, and sphene.

S.8.—Muscovite and a few phyllite fragments.

S.9.—Feldspar, mica, tourmaline, and epidote.

S.10.—Feldspar, mica, and tourmaline.

S.11. *Quartzite, Athelstone.*

Medium-grained quartzite consisting of granoblastic quartz with some orthoclase feldspar slightly kaolinized and some interstitial fine quartz, muscovite, and chlorite. Opal less than 0·01 per cent.

S.12. *Quartzite, Mitcham.*

Fine-grained quartzite consisting of quartz with some orthoclase feldspar partly kaolinized and interstitial sericite. Some phyllite fragments in the crushed sand. Opal approximately 0·1 per cent.

S.14. *Surface Gravel, Oodnadatta.*

Red quartzite gravel. The quartzite has a microcrystalline ferruginous quartz cement. Opal content may be up to 6 per cent.

S.15. *Opaline Quartzite, Coober Pedy.*

Dense grey quartzite consisting of fine quartz grains with a cryptocrystalline quartz cement containing a little opal.

S.16. and 16A. *Feldspathic Quartzite, South Para.*

Medium-grained quartzite containing considerable fresh orthoclase feldspar with some interstitial fine quartz and muscovite and a little tourmaline.

S.17. *Sand, Golden Grove.*

See S6.–10. Accessories—muscovite, tourmaline, and clay material.

Northern Territory.

NT.1. *Sandstone, Newcastle Waters.*

White to dark-red sandstone consisting of rounded quartz grains in a hard argillaceous cement with limonite and hematite.

NT.2. *Gravel, Tennant's Creek.*

Red-coated pebbles of hematite-rich sandstone with a little quartzite and basic igneous rock.

Sandstone: Varies from hematite-cemented and limonite-cemented quartz grains to almost pure hematite.

Igneous rock: Vesicular basalt with small olivine crystals in a brown glass containing feldspar microlites.

NORTHERN TERRITORY—*continued.*

NT.3. *Gravel, Tennant's Creek.*

Red-coated quartz and hematite-cemented sandstone pebbles. The sandstone consists of grains of quartz and very fine-grained quartzite, some of which is cryptocrystalline.

NT.4. *Gravel, Barrow Creek.*

Red-coated quartz, quartzite, hematite-cemented sandstone and a few igneous rock pebbles.

Quartzite: Fine-grained with considerable hematite grading into the hematite-cemented sandstone.

Igneous rock: Trachyte with a few orthoclase crystals in a greenish microcrystalline base.

NT.5. *River Gravel, Alice Springs.*

Granite and gneiss gravel.

Granite: Probably an adamellite. Quartz, feldspar (orthoclase and plagioclase), partly altered to sericite and epidote, biotite (altered to chlorite), muscovite, and ilmenite.

Gneiss: Hornblende gneiss consisting of hornblende (partly altered to chlorite and limonite), quartz, plagioclase feldspar, and epidote.

NT.6. *Gravel, Alice Springs.*

Pebbles of medium-grained quartzite containing much feldspar (mostly plagioclase) extensively altered to sericite, with a little calcite, muscovite, bleached biotite, ilmenite, and interstitial sericite and chlorite. Shows no secondary silicification or ferruginization.

NT.7. *River Gravel, Katherine.*

Red-coated quartz, quartzite, greywacke, and chert pebbles.

Quartzite: Coarse-grained with considerable hematite.

Greywacke: Grains of quartz and slate with a cement of chlorite and microcrystalline quartz sometimes with hematite.

Chert: Microcrystalline and cryptocrystalline quartz sometimes containing hematite or quartz and slate fragments.

NT.8. *River Gravel, Mataranka.*

Red-coated quartz, quartzite, red standstone, red and grey slate pebbles.

Quartz: Contains considerable hematite.

Quartzite and red standstone: Range from quartz cemented by microcrystalline and cryptocrystalline quartz, sometimes with hematite and chlorite, to quartz and slaty material cemented with argillaceous hematite.

NON-AUSTRALIAN.

Z.1. *Sand, Leighton Buzzard, England.*

Standard quartz sand.

Z.2. *Siliceous Magnesian Limestone, California, U.S.A.*

No. 28039, described by Stanton (1940).

II. The Effect of Alkali Movement in Hardened Mortar

By H. E. Vivian, B.Sc.Agr.

Summary

The movement of alkalis through hardened mortars is shown by a "composite" test-bar method. Measurements and observations made on these bars indicate that alkalis move from zones of high concentration to those of lower concentration. The effects of this movement on the reaction of alkalis with opal are discussed.

1. Introduction

Stanton (1940) showed that mortars expand abnormally when made with high-alkali cements and opal-bearing aggregates. Stanton (1940, 1943) has also shown that storage conditions affect the expansion of these mortars. Carlson (1944) has shown that increased environmental temperature accelerates the expansion rates of a number of different mortars. Although the environmental conditions necessary for mortar expansion are known, the internal changes in reacting mortar and the behaviour of alkali-compounds, especially their mobility, have not been clearly demonstrated.

Alkalis are shown here to migrate through hardened mortar. Besides having an important effect on the reaction of aggregate in mortar, the mobility of alkalis suggests that even low-alkali mortars which contain reactive aggregate may deteriorate seriously over a long period of time.

2. Materials and Method

Alkali movement through hardened mortar was studied by means of a modification of Stanton's method (1940) for testing cements and aggregates for expansive reaction. Composite test bars, consisting of a number of alternating sections of different mortars, were used. The sections were of four types, and consisted of high- and low-alkali cements with reactive and non-reactive aggregates. Each bar, which was 1 in. by 1 in. by 11¼ in., had an effective length of 10 inches between the embedded ends of the stainless steel gauge points. The water: cement: aggregate ration for each mortar was 0·45: 1: 2 by weight.

Two commercial cements were used. These contained 0·86 and 0·12 per cent. $Na_2O + K_2O$, expressed as Na_2O, and are here designated H and L respectively. Chemical analyses of these cements are given in Table 1.

TABLE 1.—CHEMICAL ANALYSES OF CEMENTS, SHOWING PERCENTAGE OF EACH CONSTITUENT.

Cement.	SiO_2.	Fe_2O_3.	Al_2O_3.	CaO.	MgO.	SO_3.	Na_2O.	K_2O.	Loss on Ignition.	Total.
H ..	21·85	2·17	6·46	63·61	0·69	2·19	0·56	0·45	2·05	100·03
L ..	23·42	5·33	4·33	61·90	0·74	1·85	0·00	0·18	2·05	99·80

The non-reactive aggregate (designated NR) was a quartz sand from Leighton Buzzard, England, sieved to — 18 + 25 B.S.S. mesh. The reactive aggregate (designated R) consisted of 10 per cent. siliceous magnesian limestone, crushed and sieved to — 18 + 52 B.S.S. mesh, plus 90 per cent. Leighton Buzzard sand.

The " composite " bars were fabricated in duplicate from separate lots of well-mixed mortar, consisting of different combinations of cement and aggregate. One end of the bar mould was filled with a 1-in. section of mortar packed tightly around the stainless steel gauge point. The free end of this section was kept approximately vertical with a glass slide until the second section was placed in the mould. Subsequent sections were placed in the mould in the same way. Care was taken to avoid undue mixing of adjoining mortars. When the mould was completely filled it was stored in a moist atmosphere at 70°F., for twenty hours. On removal from the mould, the bars were measured, stored in moist air in sealed containers, and kept at room temperature. (The yearly mean temperature in Melbourne is 58·5°F.) At first the bars were measured at intervals of two to four days, but later the time between successive measurements was gradually lengthened to a maximum period of one month. The relations of the different sections of mortar in each type of composite bar are shown in Fig. 1.

Duplicate uniform test bars, each pair consisting of only one type of mortar, were made following the normal procedure. These bars were stored under the same conditions as the composite bars.

3. Results of Test Bar Measurements

(i) *Uniform Test Bars*

Results given in Table 2 show that mortar must contain both high-alkali cement and reactive aggregate in order to expand abnormally within a relatively short period of time. Such bars expanded 0·05 per cent. in less than 28 days, and after 280 days their expansions had increased to more than 0·50 per cent. Mortars consisting of low-alkali cement and reactive aggregate did not expand abnormally, their expansions after 280 days being much lower than 0·05 per cent.

Test bars, fabricated with either cement and non-reactive aggregate, did not expand abnormally. Their expansions were lower than 0·05 per cent. after 280 days.

TABLE 2.—THE MEAN PERCENTAGE EXPANSIONS OF DUPLICATE UNIFORM TEST BARS.

Time after Fabrication (Days).	Cement H+ Aggregate NR.	Cement H+ Aggregate R.	Cement L+ Aggregate NR.	Cement L+ Aggregate R.
28	+0·001	+0·135	—0·012	—0·007
56	0·002	0·379	—0·009	—0·007
84	0·013	0·462	—0·009	—0·007
112	0·018	0·494	—0·009	—0·009
168	0·028	0·513	+0·001	+0·002
224	0·037	0·528	+0·004	+0·006
280	0·038	0·532	+0·006	+0·007

The variation in percentage expansion of the duplicate bars from their mean was less than $\pm 0{\cdot}01$ for the three low-expanding combinations and $\pm 0{\cdot}025$ for the high-expanding combination (cement H + aggregate R).

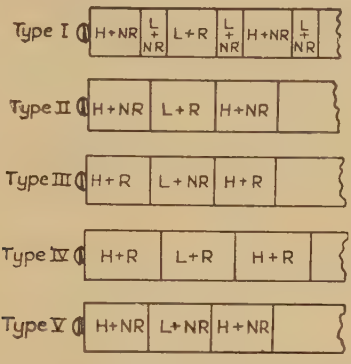

FIG. 1.—Plan of composite test bars, showing the relations of the different sections of mortar (one-quarter natural size).

Type I.—Test bar contained five sections of cement H + aggregate NR alternating with four sections of cement L + aggregate R, each ¾–1 inch long, all separated by eight sections of cement L + aggregate NR, each ¼–½ inch long.

Type II.—Test bar contained five sections of cement H + aggregate NR alternating with five sections of cement L + aggregate R. Sections were 1–1¼ inches in length.

Type III.—Test bar contained five sections of cement H + aggregate R alternating with five sections of cement L + aggregate NR, each section being 1–1¼ inches long.

Type IV.—Test bar contained four alternating sections of both cement H + aggregate R and cement L + aggregate R. Sections were 1¼–1½ inches long.

Type V.—Test bar contained five alternating sections of both cement H + aggregate NR and cement L + aggregate NR. Sections were 1–1¼ inches long.

TABLE 3.—THE MEAN PERCENTAGE EXPANSION OF DUPLICATE COMPOSITE TEST BARS.

Time after Fabrication (Days).	Type I.	Type II.	Type III.	Type IV.	Type V.
7 ..	+0·005	+0·004	+0·014	+0·016	+0·005
10 ..	0·004	0·004	0·027	0·045	0·006
13 ..	0·004	0·003	0·085	0·104	0·005
19 ..	0·001	0·002	0·197	0·181	0·006
33 ..	0·002	0·026	0·473	0·394	0·014
43 ..	+0·000	0·041	0·527	0·449	0·014
57 ..	−0·001	0·085	0·639	..	0·006
74 ..	+0·001	0·121	0·708	0·605	0·007
102 ..	+0·003	0·192	0·856	0·713	0·009
123 ..	−0·001	0·235	0·925	0·775	0·007
169 ..	+0·015	0·326	1·036	0·894	0·014
208 ..	+0·034	0·397	1·086	0·964	0·020
264 ..	+0·069	0·483	1·118	1·012	0·011

The variation in percentage expansion of duplicate bars from their mean was $\pm 0{\cdot}055$ for Types III. and IV. bars, and was $\pm 0{\cdot}02$ for Types I., II., and V. bars.

(ii) *Composite Test Bars*

Results of composite test bar expansions given in Table 3 show—

(*a*) Every type of test bar which contained reactive aggregate expanded, irrespective of whether the reactive aggregate was combined with high- or low-alkali cement. Since uniform test bars do not expand significantly unless high-alkali cement H is combined with aggregate R, it is reasonable to deduce from the expansions of composite test bars of Types I. and II. (Fig. 2) that alkalis moved from zones of high concentration (i.e., sections of cement H + aggregate NR) to zones of lower concentration (i.e., sections of cement L + aggregate R).

(*b*) The delay in commencement of expansion of composite test bars of Types I. and II. indicates that alkalis require a considerable time to migrate through hardened mortar.

(*c*) The expansion rates of test bars of Types I. and II. were lower than those of Types III. and IV. One reason for this is the difference in length of reacted mortar in the different types of test bars. In test bars of Types I. and II. the length of reacted mortar was very small, whereas in test bars of Types III. and IV. the length of reacted mortar was much greater since these bars contained sections of cement H + aggregate R each of which reacted throughout its whole length (see Fig. 2).

The percentage expansions of the composite test bars and the uniform test bar (cement H + aggregate R) have been graphed against storage time (Fig. 3).

The total expansion of uniform test bars which contain 10 inches of reactive mortar was about half that of composite test bars, Types III. and IV., which contain approximately 5 inches of reactive mortar (cement H + aggregate R). The expansions of the other composite test bars seem to be affected by their different lengths of reacted mortar. To compare the different test bars, expansions should be calculated as percentages of the actual length of reacted mortar rather than of the effective length of the bars. See Fig. 4 for the plot of these calculated results against storage time. Although the reason for these unusual expansions is not known, it seems probable that they are due to differences in amounts of available water and alkalis in the mortars. Further work on the effect of these variable factors on mortar expansion is in progress.

4. Observations on Test Bars

(i) *Uniform Test Bars*

(*a*) Test bars, consisting of cement H + aggregate R, rapidly developed surface spots and severe random cracking throughout. The surface spots were wet and transparent at first, but later become white and opaque.

(*b*) Test bars containing cement L + aggregate R developed only a very few surface spots and no random cracks.

(*c*) Test bars containing either high- or low-alkali cements and non-reactive aggregates showed neither surface spots nor cracks.

(ii) *Composite Test Bars*

In composite test bars, spotting and cracking developed only in certain areas, depending upon the combination of cement and aggregate in each section, and the combination of sections in each bar (see Fig. 2).

These observations are summarized as follows:—

Types I. and II.—Spots and cracks were confined to certain zones in cement L + aggregate R sections. These zones were in contact with adjoining sections of mortar. The width of reacted mortar in bars of Type II. was greater than in those of Type I., there being numerous cracks in each reacted zone in the former while in the latter there were only one or two transverse cracks. Since all signs of

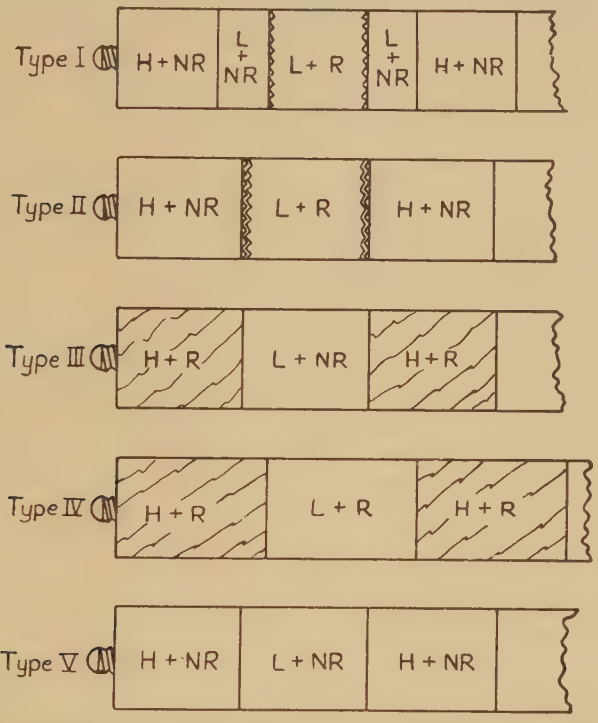

FIG. 2.—Appearance of composite test bars after storage in moist air for 264 days (half natural size).

Type I.—Reaction spots and cracks developed only at eight surfaces in each bar where sections of cement L + aggregate R and cement L + aggregate NR joined. The width of reacted mortar was 1/16–1/8 inch at each surface, and the number of visible cracks was 1 or 2.

Type II.—Reaction spots and cracks developed only at ten surfaces where sections of cement L + aggregate R joined sections of cement H + aggregate NR. The width of reacted mortar varied from 1/8–3/16 inch, and numerous cracks were visible.

Type III.—The five sections consisting of cement H + aggregate R were extensively spotted and cracked. Sections of cement L + aggregate NR showed no signs of reaction.

Type IV.—The four sections of cement H + aggregate R showed severe spotting and cracking. Sections of cement L + aggregate R showed no signs of reaction.

Type V.—No signs of reaction spots or cracks.

reaction were confined to these narrow zones, alkalis must have moved from sections of high alkali concentration to those of lower alkali concentration. Type I. bars indicate that alkalis moved through about half an inch of hardened mortar.

Since the reacted zones in both types of bars are so narrow, it appears that alkalis combine rapidly and completely with opal, and are thus prevented from further migration. Low-power microscopic examination of the interior of reacted zones of these bars showed that they were narrower in the centre of the test bar than on the surface. Thus the measurements of the average widths of reaction zones, given in Fig. 2, may be slightly high.

Types III. and IV.—The entire sections of cement H + aggregate R developed reaction spots and random cracks. The sections of cement L + aggregate NR and of cement L + aggregate R showed neither spots nor cracks.

Type V.—These bars showed no signs of reaction spots or cracks.

5. Discussion

The movement of alkalis can best be explained as due to diffusion through a system of solution-filled capillaries in the hardened cement. Diffusion in the expected direction occurs because the concentrations of alkalis in the two mortars are different.

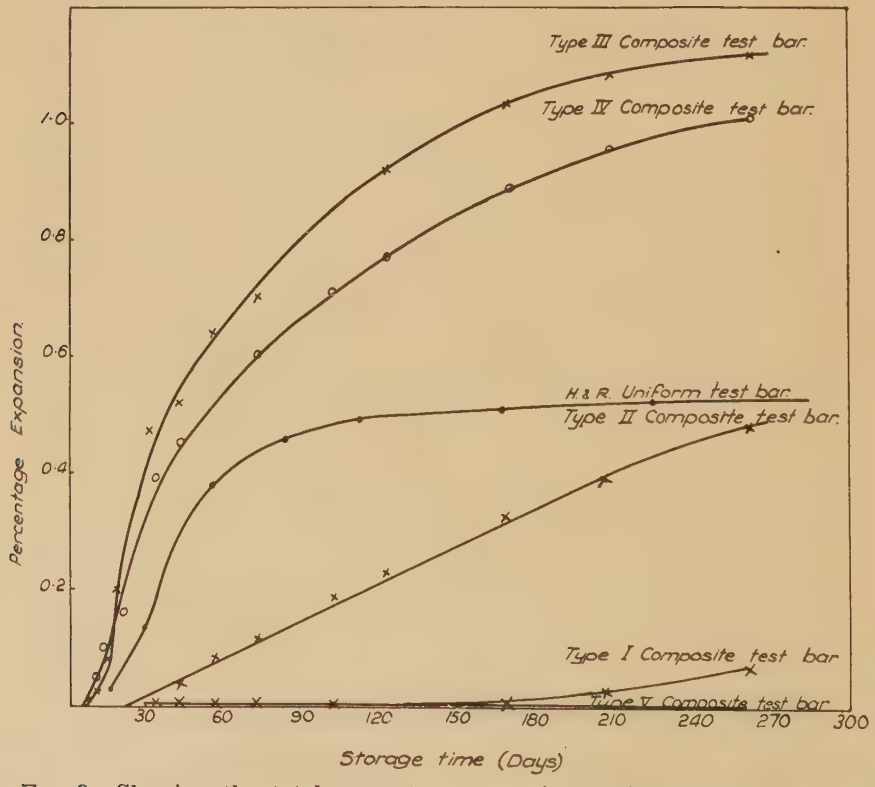

FIG. 3.—Showing the total percentage expansion against storage time of composite test bars and a reactive uniform test bar.

The comparatively long time taken for reaction to appear in bars in which the alkalis have to migrate from zones of high concentration to those containing opal suggests that the rate of movement of alkali ions and hydroxyl ions through hardened cement is slow. The channels through which these ions must move are narrow and possess large surface areas. As the concentration of diffusing ions is increased in any zone of low concentration, the number adsorbed on the capillary walls may increase. Although this would tend to maintain the rate of diffusion of ions from zones of high concentration, it also has the effect of reducing the number of ions which reach the reactive particles and, as equilibrium between diffusing and adsorbed ions is approached, the ionic diffusion rate may decrease. Alkalis may move in this way to positions where they can react with opal.

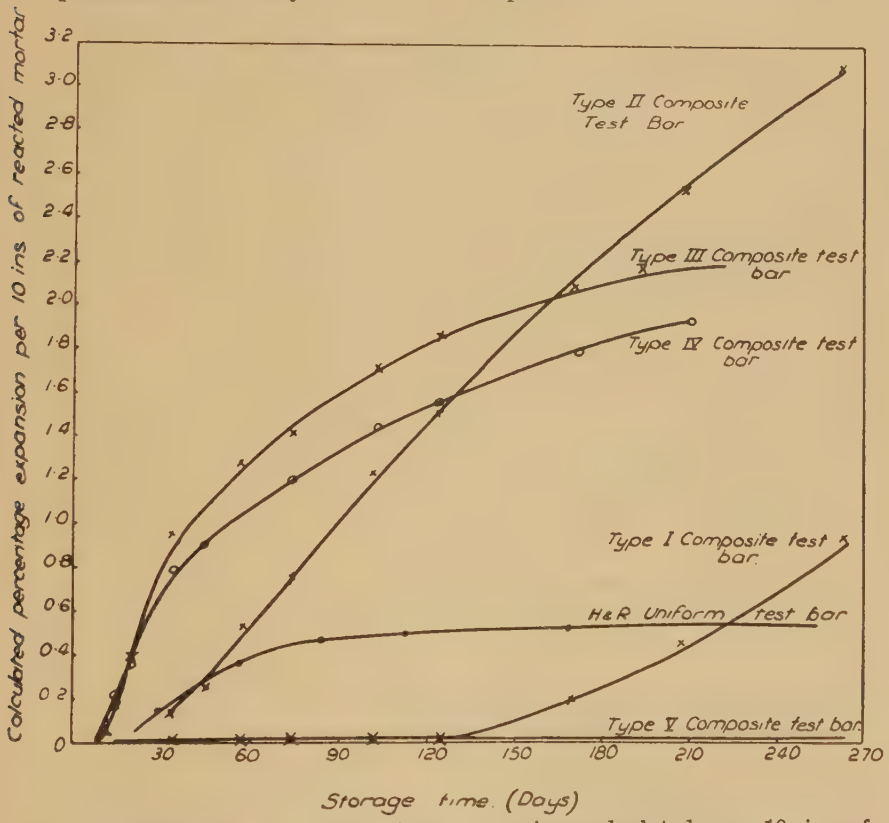

FIG. 4.—Showing the percentage expansion calculated per 10 in. of reacted mortar against storage time. The factors used for obtaining these values were:—Type I.—13·33, Type II.—6·40, Type III.—2·00, Type IV.—2·00, Type V.—1·00. Uniform test bar, 1·00.

After reacting with opal, the negatively charged hydroxyl ions will disappear from solution. Thus an hydroxyl ion concentration gradient will be established and maintained between the solution and the opal particle. Positively charged alkali ions will diffuse to the opal even though their concentration at the opal particle is equal to or greater than that in the solution, because they are necessary to maintain an electric balance with the negatively charged reacted opal. This is a Donnan effect. This diffusion of ions to the opal will continue in the

ideal case until either the available alkalis or opal is exhausted. As the number of combined hydroxyl ions increases the opal particle absorbs some of the available water from the surrounding cement, increasing its volume and thereby expanding the mortar or concrete.

These results and observations suggest several methods by which it may be possible to control serious expansive reactions. These are—

(i) Elimination of alkali solutions by reducing the water content of mortar so that no excess water remains after the cement components have been hydrated.

(ii) Combination of alkali hydroxides so that their concentrations are reduced as near to zero as possible.

(iii) Prevention of movement of interstitial water from the hydrated cement to the reacting opal particles.

(iv) Prevention of the movement of alkalis from the cement solution to the opal particles.

All these possible control measures would be difficult to accomplish in practice.

6. Conclusions

1. Under suitable environmental conditions alkalis derived from the cement are present in the solution which exists in mortar for a very considerable time after setting occurs.

2. Alkalis can migrate through hardened mortar.

3. The solution derived from the excess mixing water forms a continuous liquid medium throughout hardened mortar.

4. Although the concentration of alkalis may not be high in a mortar containing reactive aggregate, expansive reaction will probably occur over a long period of time owing to slow movement of alkalis to reacting aggregate particles, provided environmental conditions are favourable.

7. Acknowledgment

The author wishes to thank Mr. K. L. Sutherland for many valuable discussions and suggestions in connexion with this and other papers (III. and IV.) of this series.

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III. The Effect of Void Space* on Mortar Expansion

By H. E. Vivian, B.Sc.Agr.

Summary

Reaction between cement and aggregate produces expansion in mortars which are relatively compact. Mortars which contain large amounts of void space do not expand abnormally. The amount of void space depends on the proportions of water, cement, and aggregate in the mortar.

1. Introduction

In his early work on cement–aggregate reaction, Stanton (1940)† showed that maximum expansions were developed by mortars containing high-alkali cements and opaline aggregates from California when their cement: aggregate ratios were either 1 : 1 or 1 : 2 by weight. Mortars containing higher proportions of either cement or aggregate gave lower expansions. No satisfactory reason for these reduced expansions has been given, although it has been suggested that the low expansions of mortars containing high proportions of aggregate are due to the smaller amounts of alkalis which are available for reaction. A similar explanation cannot be advanced for the lower expansions of cement-rich mortars.

The experimental work described here is concerned mainly with mortars which contain high proportions of aggregate. It will be shown that the amount of void space in mortar is one of the main factors in determining its tendency to expand. As the proportion of aggregate is progressively increased in a series of mortars, the void space increases and expansion decreases to a negligible amount even though sufficient amounts of alkalis are present to react strongly with the opal particles. Expansion is also decreased by decreasing the amount of mixing water in mortar, since, as the amount of mixing water is decreased, the void space increases.

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* The term "void space" is used here to mean that part of the "pore space" which is occupied by air in the hardened mortar. The term "pore space" is applied to the total space not occupied by solids (i.e., spaces filled essentially with either water or air). The spaces occupied by water probably occur as a continuous network with small cross-sectional areas throughout the hydrated cement, whereas the spaces occupied by air are often discontinuous and have relatively large cross-sectional areas. The differences between the volumes and cross-sectional areas of spaces occupied by air and those occupied by water appear to affect the expansive properties of mortar. Although the space occupied by water may change slightly in volume as the cement hydrates, the volume of void space should not change appreciably after the cement sets. It should be noted also that there is no relationship between expansion and pore space, since the latter consists of two types of spaces, the amounts of which vary in different mortars, but always remain approximately complementary.

† Stanton, T. E. (1940).—*Proc. Amer. Soc. Civil Eng.* 66: 1781.

2. Materials and Methods

The chemical compositions of the two cements used are given in Table 1. The total alkali oxide contents expressed as sodium oxide ($Na_2O + 0{\cdot}658\ K_2O$) were 0·98 per cent. in A and 0·89 per cent. in B.

TABLE 1.—CHEMICAL ANALYSES OF CEMENTS, SHOWING PERCENTAGE OF EACH CONSTITUENT.

Cement Designation.	SiO_2.	Fe_2O_3.	Al_2O_3.	CaO.	MgO.	SO_3.	Na_2O.	K_2O.	Loss on Ignition.
A	22·14	2·38	4·94	64·12	1·08	1·84	0·45	0·81	1·88
B	21·06	2·85	5·67	63·96	0·70	2·18	0·59	0·45	2·47

Two reactive aggregates were used. Both were mixtures of opaline rock crushed and sieved to — 18 + 52 B.S.S. mesh, with non-reactive quartz sand (18–25 B.S.S. mesh) from Leighton Buzzard, England. The first was an opaline chert from California (No. 28038, described by Stanton, 1940), three parts of which were mixed with 97 parts of quartz sand; the second, an opaline rock (V17) from East Gippsland, Victoria, was mixed in varying proportions with the quartz sand.

Leighton Buzzard sand without any additions was used as a non-reactive aggregate, for control purposes.

Mortar test bars (1 in. by 1 in. by 10 in.) of the required water : cement : aggregate ratios were used for determining expansion. Small blocks of each mortar were also made, some were used for determining void space at 24 hours after fabrication, while others were broken and examined for signs of reaction at various ages up to 226 days by means of a binocular microscope at 30 diameters magnification.

Both test bars and blocks were stored in moist air in sealed containers kept at room temperature.

The volume of void space in each mortar was determined in the following way:—The total volume of each rectangular block was calculated from its linear dimensions. Uncombined water was determined by heating at 110°C. for one hour. The amounts of aggregate and hydrated cement were determined*, and from these the volumes of each were obtained. The volumes occupied by uncombined water, aggregate, and hydrated cement when subtracted from the total volume of the block gave the volume of void space, and this has been expressed as a percentage of the total volume.

The experimental results cited are for mortars which contain reactive aggregate. Mortars of similar composition, but without added reactive aggregate, neither showed signs of reaction nor expanded abnormally—none expanded more than 0·02 per cent. during the time shown.

* Hydrated cement in crushed mortar was dissolved by dilute hydrochloric acid. The undissolved sand was washed, dried, and weighed, and the difference between the weights of mortar and sand was taken as the weight of hydrated cement.

3. Experimental Work

(i) *Water Content Varied; Cement : Aggregate Ratio Constant*

Expansions of test bars are recorded in Table 2. The correlation between expansion at 226 days and percentage void space of each mortar is shown in Table 3, and is shown graphically in Fig. 1.

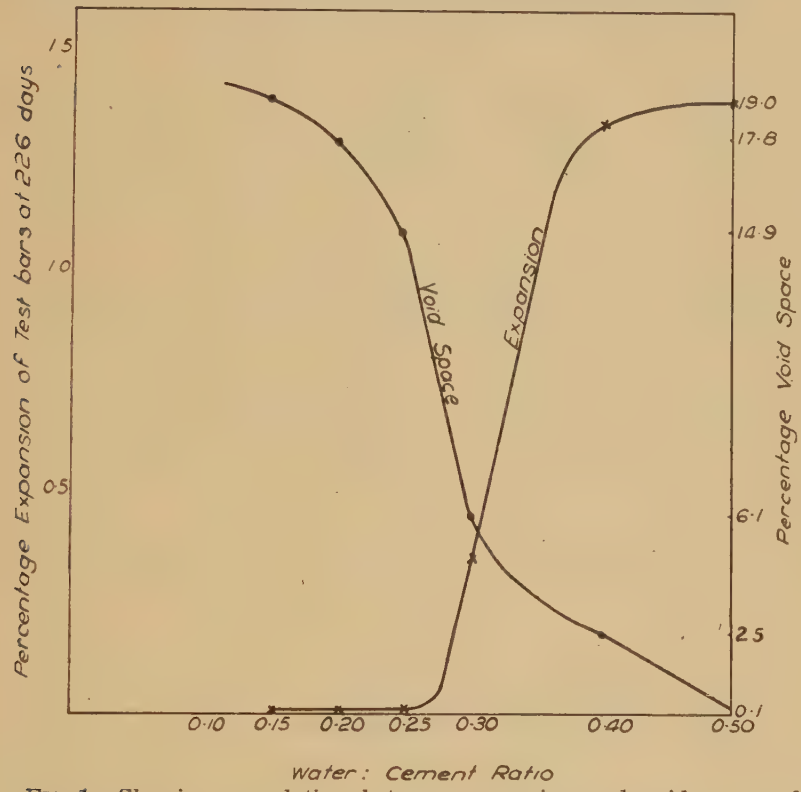

FIG. 1.—Showing correlation between expansion and void space of mortar test bars made with a uniform cement: aggregate ratio (1 : 2) and water: cement ratios as shown.

TABLE 2.—THE EFFECT OF VARIABLE WATER : CEMENT RATIOS ON THE EXPANSIONS OF MORTARS MADE WITH THE UNIFORM CEMENT : AGGREGATE RATIO OF 1 : 2 BY WEIGHT. HIGH-ALKALI CEMENT (B) AND REACTIVE AGGREGATE CONTAINING 3 PARTS OF OPALINE CHERT AND 97 PARTS OF LEIGHTON BUZZARD SAND WERE USED.

Time after Fabrication (Days).	Percentage Expansion of Mortar having the Water : Cement Ratio—					
	0·15	0·20	0·25	0·30	0·40	0·50
8 ..	+0·006	+0·003	−0·004	−0·006	+0·004	+0·012
14 ..	+0·009	+0·008	+0·003	+0·001	+0·033	+0·085
29 ..	+0·012	+0·012	+0·010	+0·024	+0·114	+0·246
44 ..	+0·010	+0·011	+0·008	+0·035	+0·244	+0·341
72 ..	+0·011	+0·011	+0·010	+0·082	+0·492	+0·651
100 ..	+0·009	+0·009	+0·009	+0·119	+0·736	+0·910
142 ..	+0·011	+0·013	+0·015	+0·195	+1·065	+1·208
170 ..	+0·012	+0·014	+0·016	+0·240	+1·172	+1·282
198 ..	+0·015	+0·013	+0·013	+0·285	+1·269	+1·359
226 ..	+0·012	+0·012	+0·016	+0·342	+1·345	+1·399

TABLE 3.—CORRELATION BETWEEN EXPANSION AT 226 DAYS AFTER FABRICATION AND VOID SPACE OF MORTAR. ALL MORTARS WERE PRESSED INTO THE MOULDS BY HAND.

Water : Cement Ratio.	Percentage Expansion.	Percentage Void Space.
0·15	+0·012	19·0
0·20	+0·012	17·8
0·25	+0·016	14·9
0·30	+0·342	6·1
0·40	+1·345	2·5
0·50	+1·399	0·1

Conclusions from this experiment are:—

(*a*) *Test bar measurements.*—(1) These mortars do not expand abnormally when the water : cement ratio is 0·25 : 1, or less.

(2) The volume of void space in mortar affects its expansion. As the volume of void space increases, mortar expansion decreases to a point when the mortar does not expand abnormally. For mortars of this composition the minimum amount of void space, which inhibits expansion, is larger than 6 but less than 15 per cent. of the total volume.

It has been found that there was a very marked increase in void space in a 1 : 2 mortar when the water : cement ratio was decreased to 0·27 : 1.

(*b*) *Observations.*—(1) Microscopic examination of broken mortar blocks showed that in all cases opal particles had been attacked.

(2) Mortars with water : cement ratios up to 0·25 : 1 contained noticeably large amounts of void space. These mortars failed to expand because the pressure of the expanding opal particles was not exerted against mortar in all directions. In cases where the reacting particles were sheathed by a thin layer of cement or mortar, the initial expansion cracked the mortar, and thereafter the reaction product escaped into a void and exerted no further pressure.

(3) Those mortars made with water : cement ratios of 0·30 : 1 and higher, which expanded significantly, were relatively compact, and the reaction product was generally confined to the site of reaction by the surrounding mortar until the mortar was cracked. The reaction product was then forced along the cracks.

(4) Only mortars with water : cement ratios 0·30 : 1 and higher showed signs of severe random cracking. These cracks were always associated with reacting opal particles.

(ii) *Aggregate Content Varied; Water : Cement Ratio Constant*

Test bars and blocks were made using high-alkali cement (A) and the reactive aggregate, consisting of opaline rock (V17), plus quartz sand (Leighton Buzzard). A constant amount of opaline rock (13 g.

per test bar) replaced an equivalent weight of quartz sand in the mixtures (*a*) to (*e*) shown below. This amount of opaline rock represents 5 per cent. of the total aggregate used in a bar of mortar with cement : aggregate ratio 1 : 2 by weight. The cement : aggregate ratios of the various mortars were (*a*) 1 : 1, (*b*) 1 : 2, (*c*) 1 : 3, (*d*) 1 : 5, (*e*) 1 : 8, and (*f*) cement plus 13 g. of opaline rock per bar without any quartz sand. Although the water : cement ratio was kept constant at 0·50 : 1, the amount of water added to each mixture decreased as the proportion of cement in the mortars decreased. It was essential that the amount of reactive aggregate in each mortar should be kept constant in order to eliminate possible expansion errors.

The percentage expansions of these test bars are recorded in Table 4. Correlation of expansion at 232 days with the volume of void space in each mortar is given in Table 5, and is shown graphically in Fig. 2.

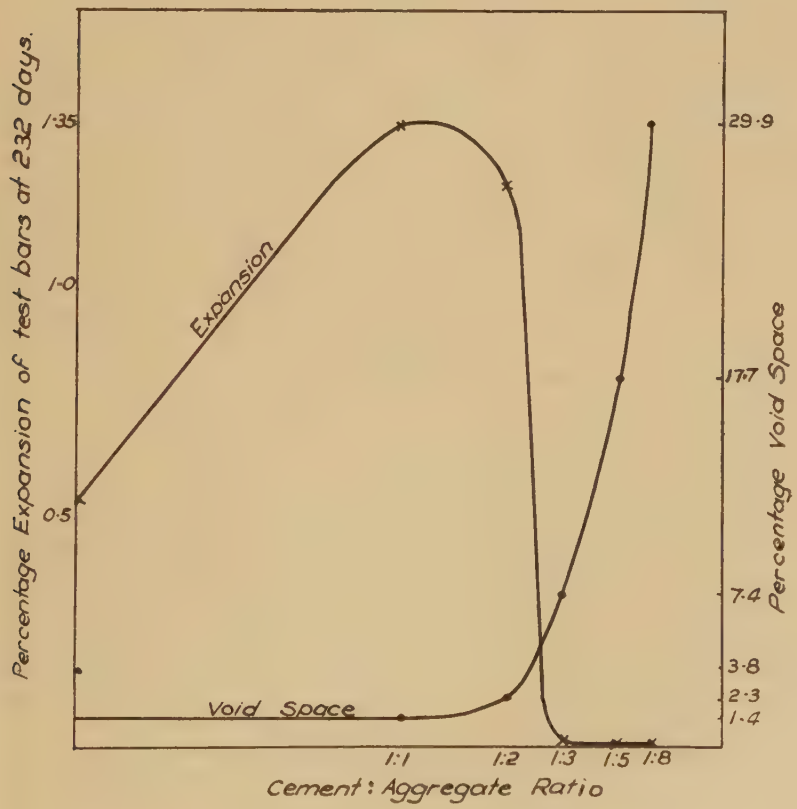

FIG. 2.—Showing correlation between expansion and void space of mortars with given cement: aggregate ratios. A uniform water: cement ratio (0·50 : 1) was used with each mortar.

TABLE 4.—PERCENTAGE EXPANSION OF MORTAR TEST BARS OF VARIABLE CEMENT : AGGREGATE RATIOS. THE AMOUNT OF REACTIVE OPALINE AGGREGATE AND THE WATER : CEMENT RATIO (0·5 : 1) IN EACH TEST BAR WERE KEPT CONSTANT.

Time after Fabrication (Days).	Proportions of Cement : Aggregate.					
	Cement.*	1 : 1	1 : 2	1 : 3	1 : 5	1 : 8
3 ..	−0·001	+0·002	+0·003	+0·004	+0·006	+0·006
10 ..	+0·010	+0·028	+0·006	+0·004	+0·009	+0·006
20 ..	+0·120	+0·223	+0·173	−0·001	+0·008	+0·007
27 ..	+0·213	+0·358	+0·310	+0·001	+0·002	+0·004
36 ..	+0·271	+0·507	+0·506	±0·000	+0·001	−0·001
43 ..	+0·304	+0·595	+0·607	−0·001	−0·002	−0·002
50 ..	+0·338	+0·660	+0·679	−0·004	−0·002	−0·002
57 ..	+0·370	+0·762	+0·751	−0·005	−0·003	−0·005
64 ..	+0·397	+0·815	+0·816	−0·005	−0·003	−0·002
78 ..	+0·430	+0·912	+0·911	−0·003	−0·003	−0·003
92 ..	+0·444	+1·022	+0·980	−0·010	−0·008	−0·005
120 ..	+0·487	+1·134	+1·055	−0·005	−0·004	−0·003
176 ..	+0·524	+1·258	+1·111	−0·007	−0·007	−0·007
232 ..	+0·539	+1·352	+1·223	−0·008	−0·006	−0·006

TABLE 5.—CORRELATION OF TOTAL EXPANSION AT 232 DAYS AFTER FABRICATION WITH VOID SPACE IN EACH MORTAR. THE WATER : CEMENT RATIO WAS KEPT CONSTANT (0·5 : 1). ALL MORTARS WERE PRESSED INTO THE MOULDS BY HAND.

Cement : Aggregate Ratio.	Percentage Expansion.	Percentage Void Space.
Cement*	+0·539	3·8
1 : 1	+1·352	1·4
1 : 2	+1·223	2·3
1 : 3	−0·008	7·4
1 : 5	−0·006	17·7
1 : 8	−0·006	29·9

Conclusions from this experiment are:—

(*a*) *Test bar measurements.*—(1) Mortars with cement : aggregate ratios 1 : 3 and lower did not expand abnormally.

(2) Expansion depends on the void space in the mortar not exceeding a given limit which in this experiment appears to be somewhat less than 7·4 per cent. of the total volume of the mortar.

(*b*) *Observations.*—(1) Microscopic examination of broken mortars revealed that in all cases opal had undergone reaction. This suggests that the failure of any mortar to expand was not due to lack of alkalis.

(2) Mortars with cement : aggregate ratios 1 : 3 and lower contained large numbers of air voids, while those with ratios 1 : 2 and higher appeared relatively compact.

* These test bars contained cement (A) and 13 grams of opaline aggregate, but no Leighton Buzzard sand. Discussion of their anomalous expansions is not attempted here since the general subject of mortar expansion will be discussed fully in later papers.

(3) Those mortars which failed to expand did so because their amounts of void space were large, and their reacting opal particles expanded into void spaces without exerting sustained disruptive pressure on the mortar.

(4) Relatively compact mortars expanded significantly. The reacting opal particles exerted pressure on the mortar itself as there were few void spaces into which the reaction product could expand.

(5) Only mortars which expanded abnormally showed severe random cracking. In all cases these cracks were associated with reacted opal particles.

(iii) *Water and Aggregate Varied; Cement Content Constant*

The same materials and cement : aggregate proportions were used as in Experiment (ii). The water : cement ratios of mortars (*a*) and (*f*) (Experiment (ii)) were not changed, but those of (*b*), (*c*), (*d*), and (*e*) were increased to 0·55, 0·65, 0·75, and 0·85, respectively.

The percentage expansions of test bars are given in Table 6. Correlation between expansion at 232 days and volume of void space in each mortar is shown in Table 7, and also shown graphically in Fig. 3.

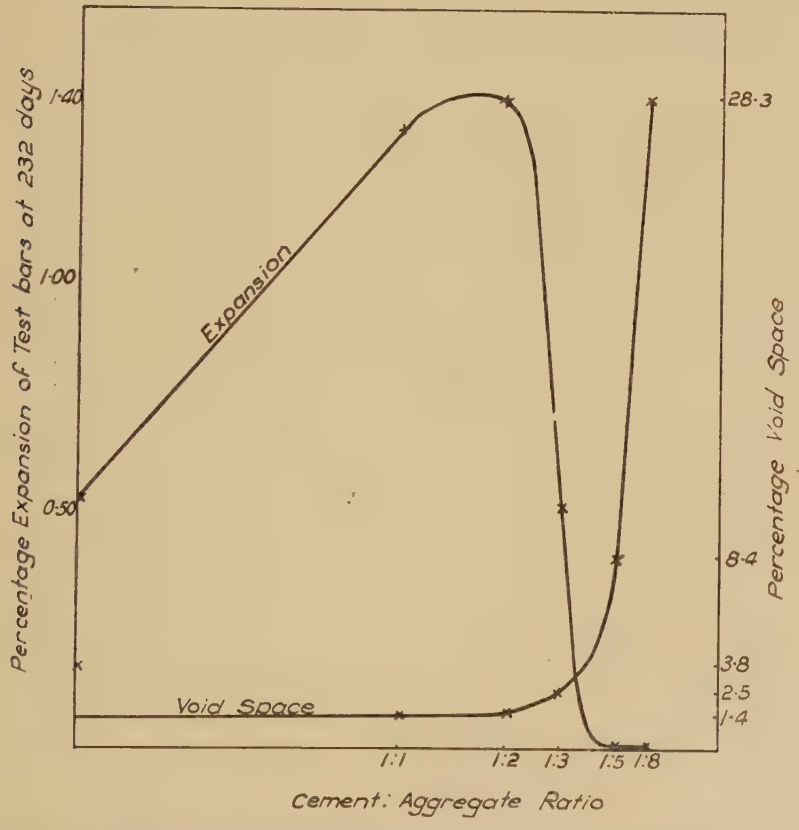

FIG. 3.—Showing the effect of increased water : cement ratios on the expansion and void space of each mortar. (Compare Fig. 2.)

TABLE 6.—THE EFFECT OF INCREASING WATER : CEMENT RATIOS ON EXPANSION OF MORTAR TEST BARS OF DECREASING CEMENT : AGGREGATE RATIOS.*

Time after Fabrication (Days).	Percentage Expansions of Mortars with the Specified Cement : Aggregate and Water : Cement Ratios.					
	Cement	1 : 1	1 : 2	1 : 3	1 : 5	1 : 8
	W./C. 0·50	0·50	0·55	0·65	0·75	0·85
3 ..	−0·001	+0·002	+0·006	+0·005	+0·004	+0·002
10 ..	+0·010	0·028	0·018	0·008	+0·007	+0·004
20 ..	0·120	0·223	0·199	0·043	+0·003	−0·002
27 ..	0·213	0·358	0·367	0·093	+0·001	−0·003
36 ..	0·271	0·507	0·576	0·173	−0·002	−0·005
43 ..	0·304	0·595	0·712	0·229	−0·004	−0·006
50 ..	0·338	0·660	0·802	0·283	−0·005	−0·006
57 ..	0·370	0·762	0·917	0·325	−0·008	−0·008
64 ..	0·397	0·815	0·975	0·354	−0·007	−0·007
78 ..	0·430	0·912	1·051	0·385	−0·008	−0·008
92 ..	0·444	1·022	1·129	0·414	−0·011	−0·012
120 ..	0·487	1·134	1·236	0·456	−0·010	−0·011
176 ..	0·524	1·258	1·277	0·480	−0·012	−0·014
232 ..	0·539	1·352	1·406	0·520	−0·014	−0·016

* The results in this table should be compared with those in Table 4.

TABLE 7.—CORRELATION BETWEEN EXPANSION AT 232 DAYS AND VOID SPACE IN MORTARS WITH INCREASED WATER : CEMENT RATIOS.* ALL MORTARS WERE PRESSED INTO THE MOULDS BY HAND.

Cement : Aggregate Ratio.	Water : Cement Ratio.	Percentage Expansion.	Percentage Void Space.
Cement	0·50	+0·539	3·8
1 : 1	0·50	+1·352	1·4
1 : 2	0·55	+1·406	1·3
1 : 3	0·65	+0·520	2·5
1 : 5	0·75	−0·014	8·4
1 : 8	0·85	−0·016	28·3

* Compare with Table 5.

Conclusions from this experiment are:—

(*a*) *Test bar measurements.*—(1) The higher water : cement ratio of mortar with cement : aggregate ratio 1 : 3 by weight reduced the void space to such an extent that this mortar expanded abnormally. (Compare with Table 4.)

(2) Mortars with cement : aggregate ratios 1 : 5 and 1 : 8 by weight did not expand significantly since they contained large amounts of void space.

(3) Mortar of cement : aggregate ratio 1 : 2 by weight developed a higher expansion than the similar mortar in Experiment (ii), probably on account of its increased water content.

(*b*) *Observations.*—(1) These were similar to those of Experiment (ii), with the exception that mortar with cement : aggregate ratio 1 : 3 by weight developed random cracks after the opal had been attacked. Most opal particles in this mortar were completely enclosed in mortar which contained few air voids.

(2) The opal particles in non-expanding mortars were attacked, but as the mortars contained large amounts of void space, the reaction product did not exert pressure on the mortar.

In order to show the general relationship between mortar expansion and void space, each expansion result at 226 or 232 days given in this paper has been graphed against the appropriate void space (see Fig. 4). Although the number of results given is small, and other factors such as the reactive aggregate used and the amount of available alkalis and water in each mortar were not constant, and although some mortars are still expanding, there appears to be an inverse relationship between expansion and void space. It can be seen also that, when the void space exceeds about 7 per cent., abnormal expansion is inhibited.

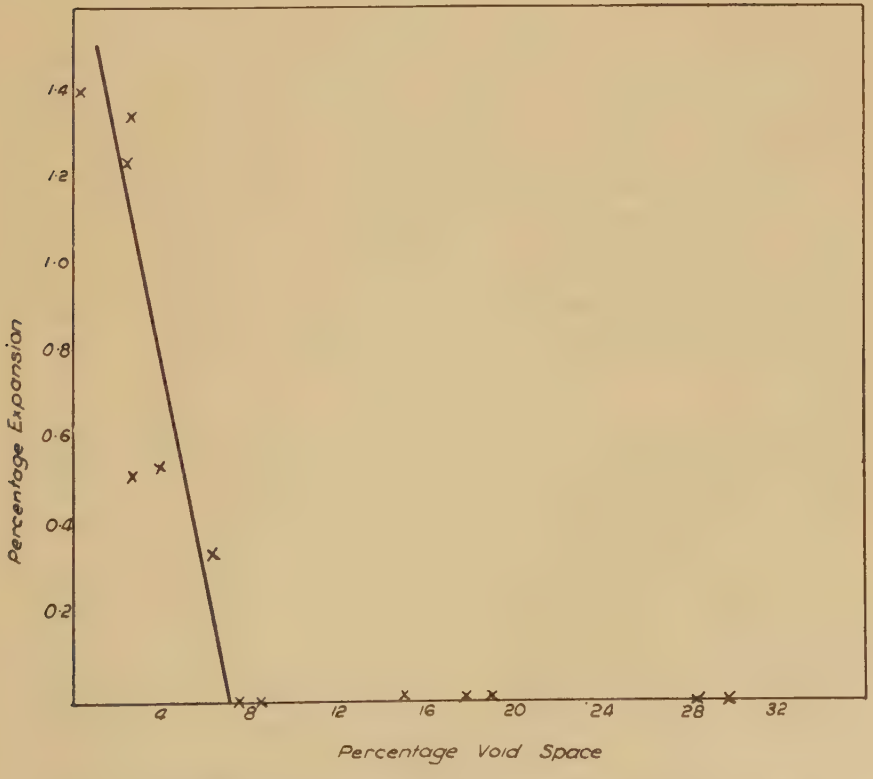

FIG. 4.—Showing the relationship between mortar expansion at 226 or 232 days and void space.

(iv) *Porous Aggregate*

A few test bars were made with high-alkali cement (A) plus a porous aggregate (V16, scoria from Mt. Noorat, Victoria). The water : cement : aggregate ratio was 0·5 : 1 : 2 by weight. Although this scoria is slightly reactive, it does not expand when used in the above proportions. Neither did it expand significantly when 3 per cent. of the scoria was replaced with an equivalent amount of opaline chert (No. 28038). Results of expansion of these mortars are given in Table 8.

TABLE 8.—PERCENTAGE EXPANSIONS OF TEST BARS CONTAINING HIGH-ALKALI CEMENT (A) PLUS POROUS AGGREGATE IN THE PROPORTION 1 : 2 BY WEIGHT.

Time after Fabrication (Days).	Containing no Opaline Aggregate.	Containing Opaline Aggregate.
28	−0·001	+0·013
56	−0·009	+0·021
84	−0·011	+0·024
140	−0·022	+0·030

The percentage void space in both mortars was 26.

Although the reactive mortar did not expand significantly, microscopic observation showed that the opal had reacted, and that the reaction product escaped into void spaces.

Further tests are in progress which indicate that when the cement : aggregate ratio is increased, a dense mortar is produced which expands abnormally. Furthermore, when the amount of mixing water is increased in a mix of cement : aggregate ratio 1 : 2, the volume of void space is decreased, but not to such an extent that the beneficial effect of voids is lost. A porous aggregate absorbs water, and thus has a similar effect on mortar to a reduction in water : cement ratio.

4. Discussion

At the time of mixing, mortar consists of three different fractions, namely, a relatively coarse solid (aggregate), a fine solid (cement), and a liquid (water). The void space of the resultant set mortar depends largely on the proportions of these three fractions and the degree to which the mortar is compacted before it sets.

A compact mortar made from the minimum amount of cement is one in which the spaces between closely-packed aggregate particles are completely filled with hydrated cement. The manner in which aggregate particles are packed determines the space which can be occupied by hydrated cement. Considering an ideal case in which the aggregate consists of spheres of uniform size packed to give (*a*) the maximum, and (*b*) the minimum amounts of space, the unoccupied volumes are approximately 47·6 and 26·0 per cent. respectively. With random packing the space would probably be between 30 and 40 per

cent. If the aggregate particles are irregularly shaped, the unoccupied space would be higher, probably 40 to 50 per cent. Thus mortars which contain large proportions of aggregate (e.g., those with cement : aggregate ratios of 1 : 5 and 1 : 8) do not contain sufficient cement to fill the spaces irrespective of their water contents. Consequently, such mortars contain large amounts of void space. If the aggregate contains particles of a wide range of sizes, mortars containing fewer voids will be obtained than when the particles are of uniform size, since some of the small particles as well as hydrated cement will fill spaces between the larger particles.

The properties of the water-cement system undergo a series of changes (described in the succeeding paragraphs) as the proportion of the two constituents is varied. These changes affect the void space in mortar. The presence of compact aggregate particles affects the behaviour of this system only slightly, but porous aggregates reduce the amount of water in the water-cement system.

In a highly-concentrated system, that is, when the amount of water added to the cement is small, the cement particles cohere strongly, forming a stiff paste which has a relatively high yield value. In mortars, the major part of the water-cement system is held as a surface coating on the aggregate particles. Under these conditions the mortar behaves as if it consists of solid particles. The amount of void space in such mortars is large, since the cement paste resists deforming pressures and the solids cannot sediment.

With intermediate amounts of water, the water-cement system becomes plastic. The particles of cement still cohere, but if subjected to pressure the paste is capable of plastic flow. Mortar of this type has a considerable amount of void space, since it behaves like a solid and, as the solid particles cannot sediment, entrapped air cannot escape from it.

With further additions of water the yield point of the system decreases progressively. A small external force overcomes the attractive forces between the individual cement particles or floccules, causing the mass to flow, but when the external force is discontinued the particles re-associate and flow ceases almost immediately. Under these conditions little air is trapped in mortar, the solid particles can sediment together, and the majority of spaces between the aggregate particles are filled completely with the cement-water system. Such mortars which, during mixing, behave as a fluid, contain only small amounts of void space.

If sufficient water is added to produce a suspension of cement particles in water, the aggregate particles in mortar will sediment at a different rate from the cement particles. Such a mortar would consist of two parts grading into each other, the lower, a cement-deficient section containing many voids, the upper, rich in cement and containing a negligible amount of void space.

In mortars containing large amounts of void space, reactive aggregate particles are adjacent to voids or are separated from them only by thin layers of mortar or of hydrated cement. As these particles react, they expand into voids immediately, or else they first crack the surrounding layer, whereupon the reaction product escapes into the adjacent void space. If opal particles expand into voids, the mortar

is not expanded abnormally, since expansive pressures are localized and not transmitted to the mortar. Consequently, in such mortars random cracks are not very extensive, and in many instances may not be apparent.

Entrainment of air in mortar may prevent serious expansion, provided the number and volume of individual air voids are sufficiently large. Unless voids of greater volume than that of the reaction product are situated close to each reactive aggregate particle, the mortar will be cracked and expanded to some extent. Any attempt to prevent expansion in this way would meet the practical disadvantage that mortar or concrete suffers a loss in strength and in compactness.

5. Conclusions

(1) Reacting aggregate particles cause expansion in compact mortars, but not in mortars which contain large amounts of void space. Thus porous concretes should not expand. In high strength, compact concretes it is necessary, therefore, to exclude reactive aggregates. However, for light-weight concretes, which are porous, there is not the same need to select non-reactive aggregates, provided the water : cement ratio is kept sufficiently low.

(2) Opaline aggregate is attacked by alkalis in both compact mortars and those containing large amounts of void space. In the latter, attack may not be so obvious.

(3) In expanded mortars, cracks are always associated with reacted aggregate particles. These cracks are always partly filled with the reaction product.

(4) Compact mortar surrounding reacting aggregate particles appears to act as a membrane which, until cracked, tends to confine the reaction product to the sites occupied by the original particles. If the reaction product escapes into void spaces it does not expand the mortar abnormally.

IV. The Effect of Expansion on the Tensile Strength of Mortar

By H. E. Vivian, B.Sc.Agr.

Summary

It is shown that when opaline aggregate reacts it produces cracks which, if sufficiently extensive, cause abnormal reductions in the tensile strength of mortar. Determination of changes in the tensile strength of mortar is suggested as a method for evaluating the possible behaviour of aggregates.

1. Introduction

In testing aggregates the value of mortar bar measurements is limited by uncertainty as to what constitutes a dangerous degree of expansion. Thus a mortar which expanded 0·50 per cent. in twelve months would be considered dangerous; one which expanded only 0·05 per cent. in the same time might seem sound but if reaction had started, it too might be dangerous. Some mortars which contain reacted aggregate but which had not expanded abnormally contain small cracks. It seemed desirable therefore to determine whether such cracks affect the tensile strength of mortar.

Fine, random cracks were observed in mortar containing high-alkali cement and reactive aggregate almost as soon as expansion started. In one instance a mortar bar made from cement containing 0·98 per cent. total alkalis ($Na_2O + 0{\cdot}658\ K_2O$), and reactive opaline chert from California showed distinct cracking when the linear expansion had reached only 0·05 per cent. (In the course of later work cracks have always been observed in mortars which contain reacted aggregate before their expansions become significant.) Microscopic examination of the mortar suggests that opal particles, after reacting with alkalis, expand with sufficient force to overcome the cohesion of the cement and to crack it. Cracks developed in this way reduce the tensile strength of mortar very considerably. Tensile strength changes in mortars may be useful for recognizing slow-expanding combinations of cement and aggregate at comparatively early ages. In addition, changes in tensile strength of mortar which contains reacting aggregate, when correlated with cracking and expansion, give important information about the mechanism of expansion.

2. Materials and Method

Chemical analyses of the three cements used are given in Table 1. Their percentage total alkali contents expressed as $Na_2O + 0{\cdot}658\ K_2O$ were (A) 0·98, (B) 0·48, and (C) 0·15.

Two different aggregates were used—(*a*) non-reactive, quartz sand from Leighton Buzzard, England, and (*b*) a mixture consisting of 5 per cent. reactive opaline rock (V17) from Butcher's Ridge, East Gippsland, Australia, plus 95 per cent. Leighton Buzzard sand.

The water: cement: aggregate ratio used throughout was 0·50 : 1 : 2.

TABLE 1.—CHEMICAL ANALYSES OF CEMENTS.

Cement Designation.	Percentage of Each Oxide.								
	SiO_2.	Fe_2O_3.	Al_2O_3.	CaO.	MgO.	SO_3.	Na_2O.	K_2O.	Loss on Ignition.
A	22·14	2·38	4·94	64·12	1·08	1·84	0·45	0·81	1·88
B	21·88	3·15	4·35	64·00	1·78	1·83	0·09	0·59	1·93
C	23·56	5·17	4·25	61·64	0·61	1·57	0·00	0·22	2·89

Mortar test bars and tensile strength briquettes were made for each combination of cement and aggregate. All test pieces were cured for 20 hours in a moist cabinet at 70° F., and when removed from their moulds were stored in moist air in sealed containers kept at room temperature. The test bars were measured at frequent intervals and after suitable periods sets of three tensile strength briquettes were broken in an Adie Tensile Strength Testing Machine. In some instances the tensile strengths within a set of three test pieces showed considerable variations, sometimes up to 100 lb. between the minimum and maximum results, but as these variations have not seriously interfered with the general trend of the results they are not considered here. Each tensile strength result represents the mean of three variates given to the nearest 10 lb. per square inch.

Freshly broken surfaces of mortar blocks were examined by means of a binocular microscope for signs of reaction and cracking.

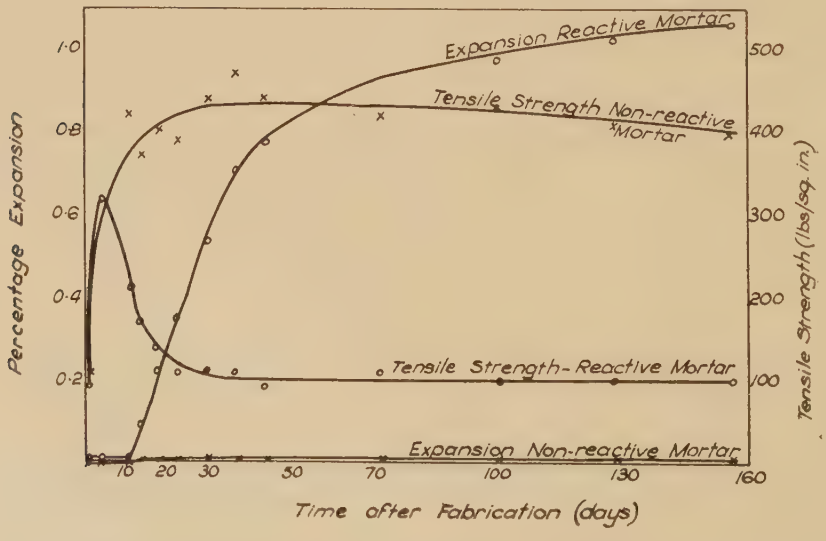

FIG. 1.—The relations between expansion and tensile strength of mortars made with high-alkali cement (A) and non-reactive and reactive aggregates.

3. Results

Table 2 shows the relation at various ages between expansion and tensile strength of mortars made from each cement and non-reactive and reactive aggregates. These relations are also shown graphically in Figs. 1, 2, and 3.

TABLE 2.—THE RELATION BETWEEN EXPANSION AND TENSILE STRENGTH OF MORTARS CONTAINING NON-REACTIVE AND REACTIVE AGGREGATES AFTER GIVEN TIMES OF STORAGE IN MOIST AIR AT ROOM TEMPERATURE.

Cement.	Time after Fabrication.	Non-reactive Aggregate.		Reactive Aggregate.	
		Expansion.	Tensile Strength.	Expansion.	Tensile Strength.
	Days.	%	lb./sq.in.	%	lb./sq.in.
High-Alkali Cement (A) ..	1	± 0·000	110	± 0·000	90
	4	+ 0·005	300	+ 0·008	320
	11	0·004	420	0·012	210
	14	0·005	370	0·089	170*
	18	± 0·000	400	0·222	140
	23	+ 0·005	390	0·351	110
	30	0·005	440	0·536	110
	37	0·004	470	0·707	110
	44	0·006	440	0·777	90
	72	0·008	420	0·928	110
	100	0·008	430	0·972	100
	128	0·011	410	1·024	100
	156	0·013	400	1·057	100
Medium-Alkali Cement (B) ..	1	± 0·000	100	± 0·000	110
	9	+ 0·001	450	− 0·015	350
	16	0·010	530	− 0·013	450
	23	0·017	450	− 0·007	420
	30	0·015	500	− 0·003	410
	35	0·002	490	+ 0·015	390
	42	0·003	500	0·080	360
	50	0·014	480	0·200	190*
	78	0·006	460	0·543	150
	106	0·018	480	0·696	90
	134	0·004	390	0·798	100
	162	0·008	430	0·824	90
Low-Alkali Cement (C) ..	1	± 0·000	90	± 0·000	100
	9	+ 0·001	310	+ 0·002	330
	28	− 0·004	460	− 0·008	490
	42	+ 0·002	510	− 0·005	420
	56	0·003	520	− 0·007	490
	70	0·001	460	− 0·009	500
	98	0·001	520	− 0·004	550*
	154	0·001	560	± 0·000	520
	241	0·003	450	+ 0·002	370
	321	− 0·001	460	± 0·000	530

* Definite cracks were observed in mortars at these ages. From later experiments it is certain that fine cracks can be detected in mortars containing either high- or medium-alkali cements at ages earlier than those shown here. Thus it is inferred that, in the above mortars, cracks were present but were not observed before the times shown.

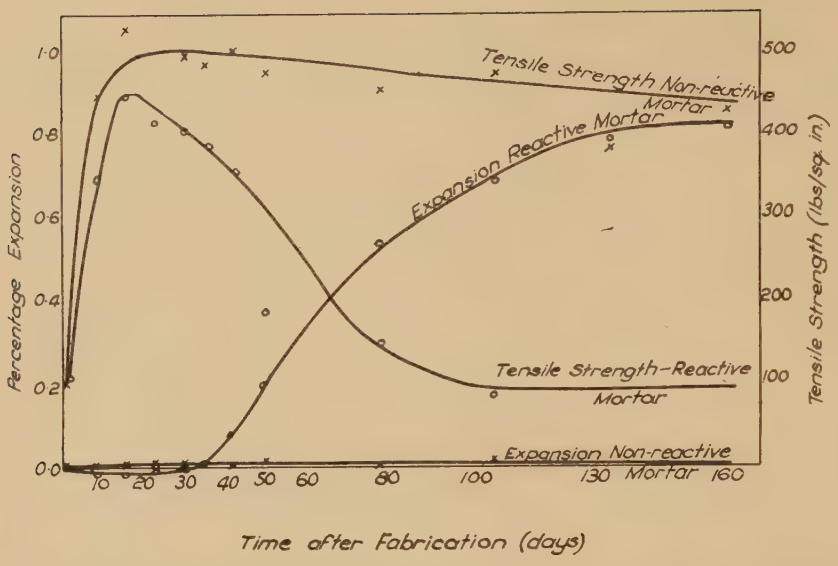

FIG. 2.—The relations between expansion and tensile strength of mortars made with medium-alkali cement (B) and non-reactive and reactive aggregates.

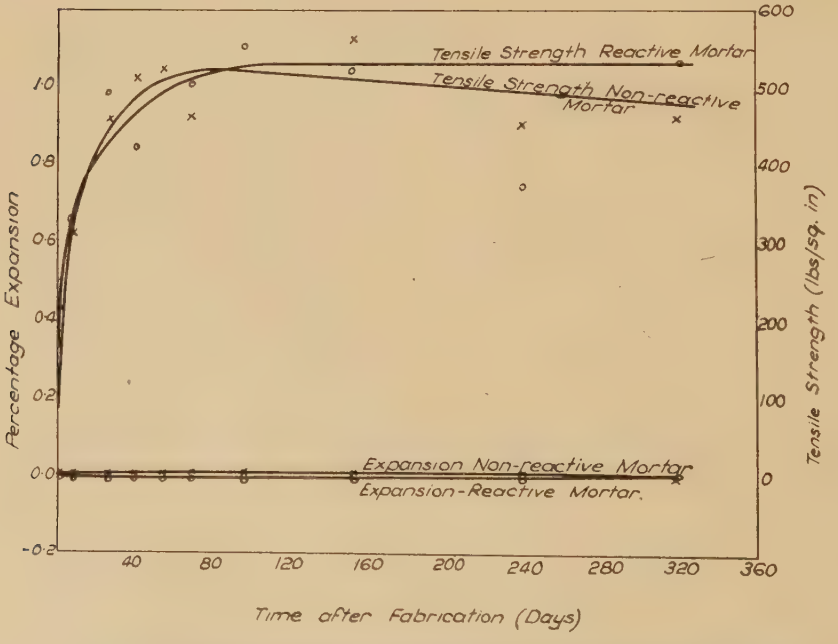

FIG. 3.—The relations between expansion and tensile strength of mortars made with low-alkali cement (C) and non-reactive and reactive aggregates.

The experimental results point to the following conclusions:—

(1) Mortars made from non-reactive aggregate and either high-, medium-, or low-alkali cement do not expand abnormally. As they age their tensile strengths at first increase but later tend to decrease slowly.

(2) Mortars made from reactive aggregate and either high- or medium-alkali cements expand abnormally and their tensile strengths increase at first and then fall more rapidly and to a greater extent than normal.

(3) The tensile strengths of such mortars begin falling while their expansions are low and continue falling as their expansions increase.

(4) Mortar containing low-alkali cement and reactive aggregate has neither expanded abnormally nor has its tensile strength decreased significantly.

Although the last-mentioned mortar may expand significantly only after two to three years' storage in moist air, it is expected that before then expanding particles will have cracked it sufficiently to reduce its tensile strength significantly.

Results of examination of mortars are summarized as follows:—

(1) Mortars which contained no reactive aggregate showed neither signs of reaction (wet spots) nor cracks.

(2) Mortars containing reactive aggregate showed signs of reaction, such as wet spots. Some reacted opal particles had softened completely.

(3) Short cracks, associated with reacting opal particles, were first observed soon after the mortar commenced expanding. In the course of later work on similar mortars cracks have been observed when expansions were less than 0·01 per cent., and before the tensile strength of the mortar began to fall abnormally.

(4) As expansion increased the cracks lengthened and widened. They were only partly filled with the jelly-like reaction product.

4. Discussion

Discussion of these results is divided into two parts. The first deals with their implications on the mechanism of mortar expansion, the second with the testing of aggregates for abnormal expansion and the possible effect of reactive aggregate in large concrete structures.

Opal particles, on reacting with alkalis, absorb water from the surrounding cement. The expansive pressure which the particles exert on the mortar becomes greater as more water is absorbed until finally it overcomes the cohesive forces of the cement. At this stage the mortar cracks, but neither its expansion nor its tensile strength is greatly affected since the cracks are still very short and fine. A series of changes in the properties of opal particles can be observed as they react and absorb water. Initially opal particles are hard but as they react with alkalis they soften gradually and swell (cracking and expanding the mortar) and eventually become jelly-like. The reaction product of alkalis and opal on expanding (by absorbing water) is

eventually forced into the cracks in the mortar and may assist in lengthening and widening them. If a large amount of gel is produced the mortar expands rapidly and its tensile strength falls abruptly. Expansion continues as long as the reaction product can absorb water and retain the property of rigidity characteristic of a gel. Since the gel exerts both hydrostatic and directional pressures, the reaction product not only expands in the plane of the crack through the mortar but also at right angles to it. If the gel absorbs too much water and loses its rigidity thus becoming a sol or a solution it ceases to expand the mortar. Sols and solutions cannot exert directional pressures and can exert hydrostatic pressures only when restrained in all directions. On this account, and also since cracks are produced in the surrounding cement before the opal particles lose their sharply defined edges, it is highly improbable that the theory—that solutions of high osmotic pressure produced by reacting opal exert expansive pressure (by absorbing water) against the cement which acts as a semi-permeable membrane—advanced by W. C. Hansen* (1944) is tenable. The swelling of a gel, however, can explain the expansion of cracked mortar.

Serious reaction of aggregate in mortar which leads to expansion can be detected in a comparatively short time by tensile strength determinations. It is also possible that slow-reacting aggregates which are not easily detected by mortar bar measurements may be detected by this method. Observations indicate that fall in tensile strength always precedes measurable expansion, and theoretical considerations (as outlined below) support this. Since Young's modulus of elasticity of cement is low (approximately 4×10^6 lb. per sq. in.) it can be seen that the amount e, by which a cement specimen can be elongated within its elastic limits by the application of a force, is very small. Furthermore the breaking strength of cement under tension is low and, as cement is not ductile, it breaks when its elastic limit is exceeded. Under a tension of about 400 lb. per sq. in. (which would probably break the specimen), a 10-in. cement or mortar bar would expand only by about 0·01 per cent. The strain set up by forces exerted by reacting aggregate particles within mortar is not the same as that produced by external tension, since expanding aggregate tends to compact the surrounding cement particles as well as to expand the mortar. Thus the actual expansion of mortar caused by reacting aggregate particles cracking the surrounding cement is probably less than that produced by an external tensile force which just breaks the mortar.

It has been suggested that large concrete structures do not show the same percentage expansions as laboratory test bars, even though the cement and aggregate used in both were derived from the same sources. This is probably due to their differences in weight since gels produced by reacting aggregate might not be able to expand massive concrete throughout even though they crack it. In test bars, as soon as the cement is cracked, the reaction product can expand and widen cracks since it is opposed by a comparatively small load. In large structures, however, the reactive aggregate must exert a force greater than that of the tensile strength of the cement plus the weight of the overlying concrete in order to produce cracks and, in order to expand

* Hansen, W. C. (1944).—*J. Amer. Concr. Inst.* 15: 213.

the concrete after cracking it, the reaction product must be capable of expanding against the weight of the overlying concrete. It is possible, therefore, that large structures will not expand throughout but cracks or serious strain might be produced internally.

Despite doubts as to whether concrete expands throughout, it is known that concrete structures which contain high-alkali cement and reactive aggregate expand and crack near their surfaces. These surface cracks increase the rate of weathering (such as by frost action) and may possibly expose reinforcing to corrosive influences. These secondary effects could contribute to the failure of concrete structures.

5. Conclusions

(1) The tensile strength of mortar which contains reactive aggregate is reduced before expansion becomes high.

(2) As mortar expands, its tensile strength continues to decrease until it reaches a fairly uniform minimum.

(3) Expansion appears to be caused by a gel rather than by a sol or a solution.

(4) Determination of tensile strength changes gives a good indication of the stability of aggregate in mortar.

V. The Effect of Void Space on the Tensile Strength Changes of Mortar

By H. E. Vivian, B.Sc.Agr.

Summary

Mortars which contain reactive aggregate and small amounts of void space, expand and decrease abnormally in tensile strength. Those mortars which contain reactive aggregate and large amounts of void space neither expand significantly nor do their tensile strengths change abnormally.

1. Introduction

Earlier papers in this series have shown the relations between void space and expansion (Part III.) and between tensile strength and expansion (Part IV.) in mortars which contain reactive and non-reactive aggregates. Reduction in tensile strength of compact mortars, which contain reactive aggregate, is caused by cracks produced by swelling opal particles. On the other hand, mortars that contain large amounts of void space, although lower in tensile strength than compact mortars, are not cracked seriously and their tensile strengths are not decreased abnormally.

2. Experimental

The materials were similar to those used previously (Part III.), high-alkali cement (A) containing 0·98 per cent. total alkalis expressed as $Na_2O + 0{\cdot}658\ K_2O$, and reactive aggregate consisting of a mixture of opaline rock (V17) from Butcher's Ridge, East Gippsland, and Leighton Buzzard sand.

For control purposes test bars and tensile strength briquettes were made containing cement only and cement and Leighton Buzzard sand in the proportions 1 : 1, 1 : 2, 1 : 3, and 1 : 5. To determine the effect of reactive aggregate a constant amount of opaline rock (equal to 5 per cent. of the total aggregate used in a 1 : 2 mortar) was added to each mixture, replacing an equivalent weight of Leighton Buzzard sand where possible. A constant water : cement ratio, 0·50 : 1, was used. All test pieces were stored in moist air, in sealed containers kept at room temperature.

The relations between expansion and tensile strength at various ages are shown for each mortar in Table 1. Each recorded tensile strength is given to the nearest 10 lb. per sq.in., and represents the mean of three determinations. The differences between the maximum and minimum results within each group of three were 40-80 lb. per sq.in. for non-expanded mortars and 20-30 lb. per sq.in. for expanded mortars. These differences seemed to be due to chance variations in the test pieces and do not affect the general trend of the results.

TABLE 1.—THE RELATIONS AT VARIOUS AGES BETWEEN EXPANSION AND TENSILE STRENGTH OF MORTARS CONTAINING DIFFERENT PROPORTIONS OF HIGH-ALKALI CEMENT (0·98 PER CENT. TOTAL ALKALIS) AND AGGREGATES AS SHOWN.

Cement.	Time after Fabrication.	Non-Reactive Aggregate.		Reactive Aggregate.	
		Expansion.	Tensile Strength.	Expansion.	Tensile Strength.
	days.	%	lb./sq. in.	%	lb./sq. in.
Cement* (Void Space about 3·8 per cent.)	1	±0·000	150	±0·000	150
	8	−0·017	360	−0·012	310
	10	−0·010	370	−0·003	260
	13	−0·020	320	+0·040	200
	17	−0·027	340	0·130	160
	24	−0·029	340	0·316	130
	31	−0·029	260	0·417	120
	38	−0·028	310	0·498	110
	52	−0·026	260	0·558	110
	80	−0·015	350	0·623	110
	108	−0·009	270	0·657	110
	136	−0·010	200	0·680	120
	164	−0·003	250	0·692	140
Cement : Aggregate Ratio, 1 : 1 (Void Space about 1·4 per cent.)	1	±0·000	150	±0·000	150
	7	−0·004	480	+0·004	310
	12	−0·005	430	0·077	200
	19	−0·006	440	0·320	120
	26	−0·007	490	0·541	110
	33	−0·005	440	0·715	110
	40	−0·003	500	0·802	100
	54	−0·004	470	0·909	90
	82	±0·000	480	0·997	100
	110	+0·005	430	1·004	130
	138	0·009	470	1·014	120
	166	0·010	400	1·045	120
	194	0·012	380	1·080	110
Cement : Aggregate Ratio, 1 : 2 (Void Space about 2·3 per cent.)	1	±0·000	110	±0·000	90
	4	+0·005	300	+0·008	320
	11	0·004	420	0·012	210
	14	0·005	370	0·084	170
	18	±0·000	400	0·222	140
	23	+0·005	420	0·351	110
	30	0·005	420	0·536	110
	37	0·004	470	0·707	110
	44	0·006	440	0·777	90
	72	0·008	420	0·928	110
	100	0·008	430	0·972	100
	128	0·011	410	1·024	100
	156	0·013	400	1·057	100

* The control mortar consisted of neat cement without any aggregate. The mortar which contained reactive aggregate (approximately 3·3 per cent. opaline rock) had no Leighton Buzzard sand in it.

TABLE 1.—*continued.*

Cement.	Time after Fabrication.	Non-Reactive Aggregate.		Reactive Aggregate.	
		Expansion.	Tensile Strength.	Expansion.	Tensile Strength.
Cement : Aggregate Ratio, 1 : 3 (Void Space about 7·4 per cent.)	1	±0·000	140	±0·000	90
	5	+0·007	380	+0·005	380
	10	0·011	360	−0·001	350
	17	0·012	350	−0·001	350
	24	0·016	340	−0·001	360
	31	0·015	370	+0·001	300
	38	0·010	390	+0·002	320
	52	0·012	370	−0·002	360
	66	0·010	430	+0·002	300
	80	0·018	360	0·005	340
	108	0·026	330	0·011	340
	136	0·019	290	0·009	260
	178	0·023	290	0·011	300
Cement : Aggregate Ratio, 1 : 5 (Void Space about 17·7 per cent.)	1	±0·000	80	±0·000	90
	6	−0·001	210	−0·003	180
	13	+0·002	190	−0·011	240
	22	±0·000	190	−0·018	220
	29	+0·001	190	−0·006	220
	36	0·002	200	−0·006	240
	50	0·007	250	−0·005	240
	78	0·005	220	−0·002	240
	106	0·006	250	−0·002	230
	134	0·004	200	−0·012	190
	162	0·006	180	−0·007	190
	190	0·001	180	−0·007	210
	218	0·009	150	−0·013	180

3. Conclusions

The conclusions from these results are:—

(i) Control mortars which contained only non-reactive aggregate neither expanded nor changed in tensile strength abnormally.

(ii) Only mortars which expanded abnormally showed abnormal tensile strength changes. Those mortars which contained reactive aggregate but which did not expand significantly showed no abnormal tensile strength changes.

(iii) With the water : cement ratio (0·50 : 1) used in this experiment only mortars with high cement: aggregate ratios (1 : 2 and higher), which contained small amounts of void space, expanded abnormally. Mortars with low cement: aggregate ratios (1: 3 and 1: 5), which contained relatively large amounts of void space, did not expand abnormally.

These conclusions are supplemented by some observations:—

(i) Mortars which expanded abnormally also cracked excessively. The cracks, which were associated with reacting opal particles, contained some reaction product.

(ii) In all mortars which contained reactive aggregate the opal had reacted. Those mortars that did not expand abnormally were only slightly cracked since the reaction product escaped into void spaces.

(iii) The reaction product appeared to be more fluid in mortars (1 : 3 and 1 : 5) which contained large amounts of void space than in the comparable mortars (1 : 1 and 1 : 2) which contained only small amounts of void space.

(iv) Cracks were first observed in some mortars (cement plus reactive aggregate only and the 1 : 1 mortar which contained reactive aggregate) before their expansions had reached 0·01 per cent.

4. Discussion

Reacting opal particles in mortars which contain small amounts of void space cause extensive cracking and abnormal reductions in tensile strength. Cracks in mortars which contain large amounts of void space are usually very short since in most instances they lead directly to voids and do not seem to cause serious reductions in tensile strength. These mortars do not expand abnormally because the reaction product escapes into voids and thus does not exert expansive pressure on the mortar as a whole. The increased mobility of the reaction product in these mortars—a condition which is probably due partly to the higher water absorption rate of gel subjected to relatively low pressures and partly to the large void surfaces from which water can be obtained as vapour—facilitates its movement into voids and reduces its tendency to widen cracks.

The relations between the system of cracks developed in the mortar and the numbers of voids and reactive aggregate particles are now discussed. Mortars which contain many discontinuous voids with total volume slightly greater than 7 per cent. of the volume of the mortar and relatively few reactive particles, do not change abnormally in tensile strength since no system of continuous cracks is developed. If, however, the number of voids were kept constant and the number of reactive particles were increased, a point should be reached where, provided the reactive aggregate could expand sufficiently, the tensile strength of the mortar should fall abnormally on account of the increased probability of a continuous system of cracks being developed from one reacting particle to another and from void to void.

However, as the void space is increased it changes from a discontinuous to a continuous state. This change increases the internal surface of the mortar and consequently the probability that an increased number of reactive particles are situated either on or very close to these surfaces—positions where they cause only slight cracking but neither significant expansion nor abnormal reductions in tensile strength.

VI. The Effect of Carbon Dioxide

By A. J. Gaskin, M.Sc.

Summary

Expansion and spotting of mortar due to cement-aggregate reaction can be inhibited by treatment of the mortar with carbon dioxide. Active alkali hydroxides, produced by hydrolysis of the cement particles, are thereby converted to carbonates, which are inactive in contact with most aggegrates. Where carbonation is sufficiently advanced, enough protective calcite is formed to confer permanent immunity from expansion and spotting on the mortar, although no appreciable improvement in tensile strength could be obtained.

1. Introduction

A considerable amount of information has been published in the last few years concerning the deleterious effects produced in concretes by the slow reaction of certain rock aggregates with cements containing appreciable quantities of the alkali metals sodium and potassium. Details of the reactions concerned, and the effects produced by them, may be found in the publications listed in the comprehensive reviews of Alderman (1943) and Blanks (1943).

Although methods of determining the potential reactivity of aggregates have now become well established, there is as yet little information available regarding satisfactory methods of safeguarding concrete in which it has been necessary, for economic reasons, to include a potentially reactive aggregate, or of slowing up the progress of the cement-aggregate reaction once it has begun in a completed concrete structure.

Experiments were conducted by Meder (Stanton *et al.*, 1942), in which various substances were added to concrete in the mixing stage in an attempt to eliminate alkali hydroxides, which were regarded as the most reactive compounds released during hydration of alkali-rich cement and, therefore, those most likely to attack the aggregate. With the exception of aluminium powder and certain pozzolanic materials, none of the addition reagents had any beneficial effect.

The work of Bean and Tregoning (1944) has since confirmed the idea that aggregates are attacked by alkalis only when the latter are present in the form of hydroxides. Alkali-metal carbonate and sulphate solutions did not affect the opaline type of reactive aggregate, even at a temperature of 122° C. From these data it seemed probable that alkali-aggregate reaction would be inhibited if the alkali-metal hydroxides could be converted into the corresponding carbonates or sulphates as they became available for reaction in the concrete and held in the form of these salts.

It was not possible to predict whether the process could be carried to the stage where the treated concrete would remain inactive if carbonation or sulphation were discontinued.

2. Experimental

A series of experiments was undertaken in an attempt to find the simplest and most effective means of ensuring that the alkali metals were present in concrete as salts only, and not as hydroxides.

Since a certain amount of alkali-metal hydroxide appears to be produced in concrete by the slow hydrolysis of the corresponding silicates of the cement, it was assumed that any treatment designed to convert the hydroxide into an inactive salt would have to be operative throughout at least part of the time during which this hydrolysis was producing appreciable fresh hydroxide. Tests were therefore arranged to indicate the amount of salt-forming materials that would have to be supplied to the concrete, and the length of time during which this supply had to be kept up, in order to reduce the amount of alkali hydroxide below the concentration necessary to produce appreciable expansion due to alkali-aggregate reaction.

3. Preliminary Tests

Trials showed that the addition of unstable carbonates and bicarbonates to a mortar at the time of mixing was impracticable owing to the large quantity of reagent necessary to generate sufficient carbonic acid to convert the alkali-metal hydroxides to carbonates. Most of the CO_2 was used in the formation of calcium carbonate by reaction with the calcium hydroxide produced by hydrolysis of the calcium silicates and aluminates contained in the cement.

Tests were thereafter restricted to carbonation and sulphation of freshly-set mortar test bars by gaseous CO_2 and SO_2. Such tests showed that SO_2 was ineffective because of the rapidity and completeness of the reaction between this gas and moist cement. The outer surface of moist test bars exposed to SO_2 immediately became converted to a mass of coarse calcium sulphate and sulpho-aluminate crystals possessing no mechanical strength. Deterioration spread throughout the mortar as the gas penetrated the mass.

No deleterious effects were noted when freshly-set mortar bars were immersed in CO_2. It had been expected that carbonation crazing would develop, as described by Lea and Desch (1940, p. 326), but such an effect did not appear where fresh mortar was stored in a water-saturated CO_2 atmosphere.

One of the most interesting features of carbonation of mortar was revealed by the preliminary tests, namely that test bars containing reactive aggregate could be removed from storage in moist CO_2 after a few months and stored in moist air without developing spotting or expansion due to alkali-aggregate reaction (Fig. 1).

This appears to be due to the formation of protective shells of calcium carbonate around both the aggregate grains and any remaining unhydrolysed cement particles, thus isolating the aggregate from the alkali-metal hydroxide present in the solution phase of the mortar, and coating the remaining cement particles so that the production of more alkali-metal hydroxide by hydrolysis and double decomposition is largely checked.

Under the microscope thin sections of the carbonated mortar showed that much of the intergranular cementing material was present as calcium carbonate in the form of crystalline calcite. Since the mortar was allowed to set in moist air for 24 hours before being transferred to CO_2 storage, appreciable quantities of the normal suite of hydrous aluminates and silicates had already formed before carbonation started.

In general, the preliminary tests showed that treatment with CO_2 was, under certain conditions, an effective method of preventing the development of alkali-aggregate reaction in concrete. In order to define the treatment conditions more satisfactorily, three series of mortar test bars were subjected to CO_2 treatments designed to indicate the optimum conditions for "protective carbonation."

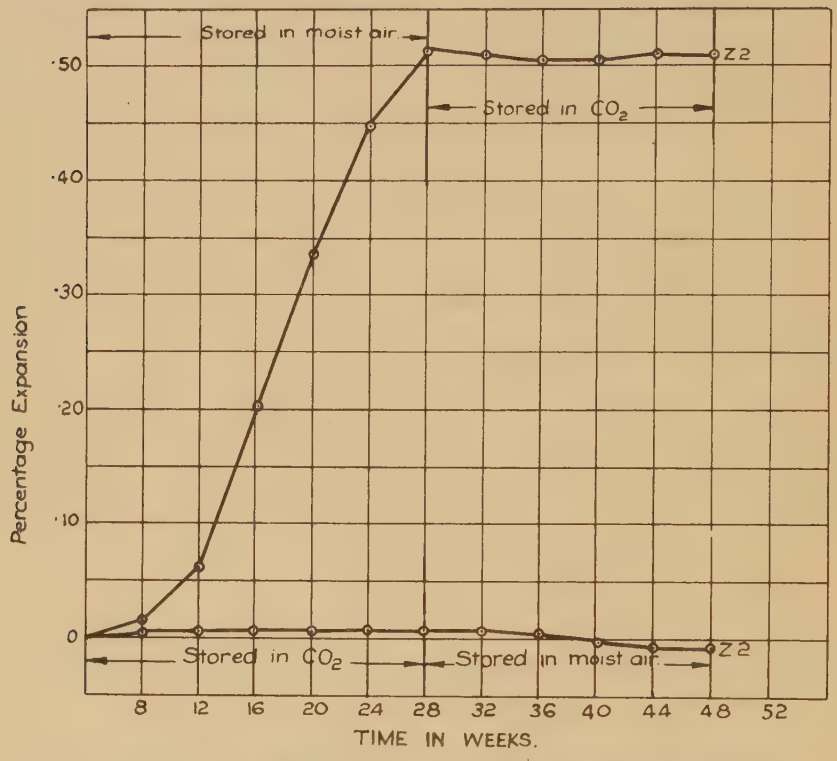

FIG. 1.—Showing the effect of carbonation on the expansion of bars containing high-alkali cement and reactive aggregate (Z 2).

4. Test Bar Experiments

Series 1: Time of Storage

In order to obtain data on the length of time of carbonation necessary to build up effective shells of calcite around grains of a typical reactive aggregate, a series of 10 in. by 1 in. by 1 in. test bars was made up, allowed to set in moist air, and subsequently stored in moist CO_2. Individual bars were removed at intervals and stored in moist air.

In this, and all subsequent test bar series, the mortar used had a water-cement-aggregate ratio of 0·6 : 1 : 2. The cement used contained 0·51 per cent. Na_2O and 0·88 per cent. K_2O. The aggregate consisted of 5 per cent. siliceous magnesian limestone from California (sieved between 18 and 52 B.S. mesh sieves, mixed with 95 per cent. quartz sand (18-25 mesh) from Leighton Buzzard. Control bars contained only Leighton Buzzard sand as aggregate.

The method of carbonation used in this and all subsequent test bar series involved only complete immersion of the bars in a sealed container filled with moist CO_2 and kept at room temperature. Extra CO_2 was added at weekly intervals in order to replace that consumed, thereby maintaining the pressure at about one atmosphere.

Results.—Test bars cured in moist air at 21° C. for 24 hours and subsequently stored in moist CO_2 for periods as long as ten days showed that for those removed from the moist CO_2 and stored in moist air, the usual expansive reactions developed. The expansion which had developed in such bars three months after fabrication was practically the same in all cases, i.e. an overall expansion of at least 0·2 per cent.

Test bars stored for 28 days in CO_2 expanded 0·01 per cent. during this period, after which they showed no further expansion, even when stored in moist air for nine months subsequent to carbonation. Indications are, therefore, that carbonation is an effective preventative of the expansive reaction if applied over a period of at least a month.

Series 2: Concentration of CO_2 During Treatment

It was apparent from preliminary tests that the expansion due to reaction of alkali-bearing cement with aggregate could be prevented by immersing the mortar test pieces in pure CO_2 saturated with water vapour. Because of the difficulty of completely replacing the air contained in a large mass of mortar with pure, moist CO_2, the minimum effective concentration of CO_2 was determined.

Test bars identical with those of Series 1 were allowed to set and cure in the moulds for 24 hours in moist air. Bars were then removed from the moulds and placed in storage vessels supplied with air-CO_2 mixtures at atmospheric pressure for 28 days.

Results.—Test bars stored in atmospheres containing up to 50 per cent. of CO_2 (by volume), when removed at 28 days and stored in moist air, subsequently developed the normal amount of expansion. It was found that expansion during and subsequent to carbonation could be effectively prevented only when the concentration of CO_2 in the treatment atmosphere was of the order of 90 per cent. by volume. It seems necessary to assume that the protective calcite layers must be formed quickly and completely. If their formation is as slow as that of the normal suite of hydrous silicates and aluminates, the latter will develop in the calcite shells and destroy both their impermeability and the protection which these shells give to the aggregate particles.

Series 3: Amount of CO_2 Absorbed

The tests concerned with the concentration of CO_2 necessary to produce protective calcite shells in potentially reactive mortar were arranged to indicate the actual quantity of CO_2 required to carbonate the mortar effectively. Since the composition and particle size of the cement would necessarily have considerable influence on the amount of CO_2 that could be absorbed by a mortar in the 28-day carbonation period required, the results obtained here are of interest only in so far as they give an indication of the order of magnitude of the quantities of CO_2 involved in the process of protective carbonation of concretes.

Results.—Test bars measuring 10 in. by 1 in. by 1 in. containing 130 g. of cement in a mortar of water-cement-aggregate ratio of 0·6 : 1 : 2 were found to absorb approximately 4 grams of CO_2 during a 28-day storage period, a large fraction of the gas being absorbed during the first few days of storage, after which little more CO_2 was taken up by the bars. The CO_2 was saturated with water vapour, at atmospheric pressure, and at a mean temperature of 22° C. Bars stored in atmospheres containing only 1 per cent. by volume of CO_2 in moist air showed an absorption of from 2-3 grams of CO_2 in 28 days. The absorption in this case was relatively slow, but continuous throughout the storage period.

5. Tensile Strength Tests

A series of ten standard 1 in. by 1 in. tensile strength test pieces was made up and allowed to set in moist air for 24 hours, then stored in moist CO_2 for a further six days. The series comprised five pieces containing high-alkali cement with standard sand, and five pieces containing the same cement with a mixture of 90 per cent. standard sand and 10 per cent. of an opaline aggregate (V.17) known to be highly reactive.

A control series of ten similar test pieces was made at the same time and allowed to mature in moist air for the full seven days. Both series were broken under similar conditions at the end of the seventh day.

Results

Test I.—Test pieces containing only standard sand and high-alkali cement were not greatly affected by carbonation, failure in tension occurring generally in the range of 400-450 lb. per square inch for both carbonated and air-stored specimens.

Test pieces containing the reactive aggregate showed the expected abnormal decrease in tensile strength in the case of both carbonated and air-stored specimens. Failure generally occurred in the range of 300-350 lb. per square inch.

It was provisionally assumed that alkali-aggregate reaction occurred at the surface of the aggregate particles during mixing and the subsequent 24 hour air-storage period, causing decrease in bond strength and a consequent drop in overall tensile strength values for test pieces containing opal. A second experiment was therefore undertaken, in which the test pieces were carbonated immediately mixing was complete, i.e. the moulds were filled with mortar and placed in the CO_2 containers.

Test II.—As in the earlier experiment the strength of the carbonated opal-bearing test pieces was no higher than that of the air-stored specimens.

It was concluded that the supply of CO_2 to the inner parts of a test piece was inadequate in both the above trials, to prevent slight alkali-aggregate reaction from forming gel films over the surface of the aggregate particles. Swelling pressures developed by the gel are assumed to cause micro-cracking and consequent decrease in tensile strength of the mortar, as described* elsewhere in this Bulletin.

* See Paper IV., p. 71.

6. Discussion and Conclusions

(i) *Expansion*

The experimental results described in the preceding section confirm the expectation, based on theoretical considerations, that the presence of excess CO_2 would prevent the expansion of mortar caused by interaction between the aggregate and alkalis derived from the cement. The test results also showed that expansion-producing reactions could be held up indefinitely if carbonation of the mortar could be effected with sufficient rapidity. The effect is apparently due to the formation of relatively impermeable protective shells of calcite around the particles of reactive aggregate. If the treatment atmosphere contains a low proportion of CO_2 mixed with an excess of moist air, a considerable amount of the hydrated silicates and aluminates normally present in air-cured cement is formed and alkali-aggregate reaction is not inhibited. It seems probable that the failure of carbonation in this case is due to the fact that the hydrate crystals are being formed at a rate comparable with the rate of formation of the calcite shells, so that the latter are continually being disrupted, and never become impermeable enough to restrict the migration of alkali-bearing solutions from hydrating cement particles to grains of reactive aggregate.

The fact that protective carbonation may be effected in 28 days under water-saturated conditions suggests that the process would be effective in a rather shorter time under drier conditions, as it is known (Lea and Desch, 1940, p. 327) that carbonation proceeds more slowly as the water content of concrete rises.

Apart from the main points mentioned above, there are two practical aspects of carbonation treatment that have been of interest during the investigation:—

(*a*) "Carbonation crazing" was not observed in any of the tests. Although previous workers have described shrinkage effects accompanying carbonation, neither overall contraction of test bars nor surface contraction (crazing) was produced by carbonation in the present investigation. The only change consistently associated with carbonation was a slight expansion (up to 0·01 per cent.) which occured in every test bar irrespective of the type of aggregate used.

(*b*) The dimensional stability of any carbonated mortar appears to be appreciably better than that of similar mortar cured in moist air. This effect is well shown when monthly measurements of carbonated test bars are compared with those of air-cured bars. The carbonated bars were stored in moist air under the same conditions of temperature and humidity as untreated test bars. Over a period of nine months the net length change shown by the carbonated bars was only +0·003 per cent., whilst air-cured bars showed length increments of 0·03-0·04 per cent. (see Fig. 2).

(ii) *Tensile Strength*

Although treatment with moist CO_2 prevented expansion of concretes subject to alkali-aggregate reaction, it was found to be ineffective in preventing the abnormal decrease in tensile strength

characteristic of such concretes. This is probably due to the fact that the method of carbonation used in the tests (i.e. diffusion of CO_2 at atmospheric pressure into the moist concrete), is relatively slow. Whilst rapid enough to prevent the formation of large quantities of silicate gel and consequent expansion and disruption of the mortar, diffusion at this pressure apparently did not prevent small quantities of free alkali hydroxide from persisting in the liquid phase of the mortar.

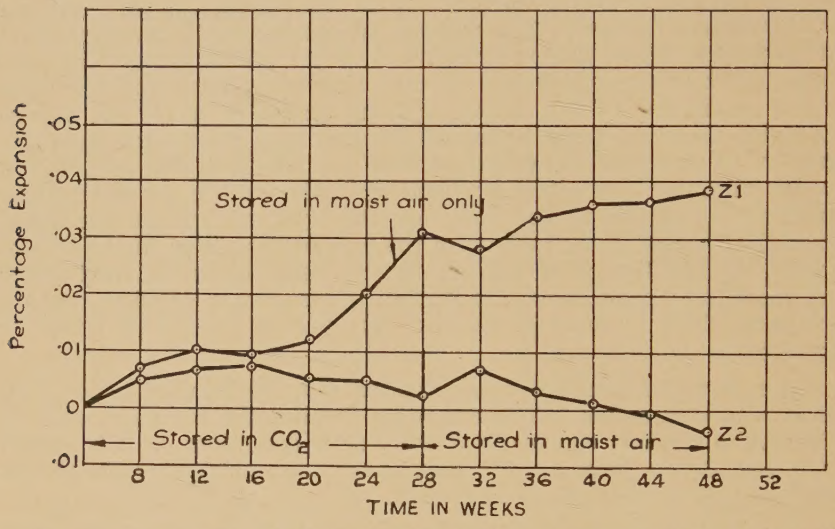

FIG. 2.—Comparison of dimensional stability of carbonated mortars (Z2) with that of an air-cured mortar containing the same cement and standard sand (Z1).

Reaction between this small amount of hydroxide and the reactive aggregate particles apparently produced sufficient gel to cause micro-cracking throughout the mortar and abnormal lowering of its tensile strength.

Although carbonation at higher CO_2 pressures has not yet been investigated, the more rapid neutralization of alkali hydroxide which could thereby be effected might provide a means of preventing abnormal reduction of tensile strength.

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186. The General Ecological Characteristics of the Outbreak Areas and Outbreak Years of the Australian Plague Locust (Chortoicetes terminifera Walk.)

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